NEW WORKS ON PHYSICS

GILLET AND ROLFE

PHILOSOPHY

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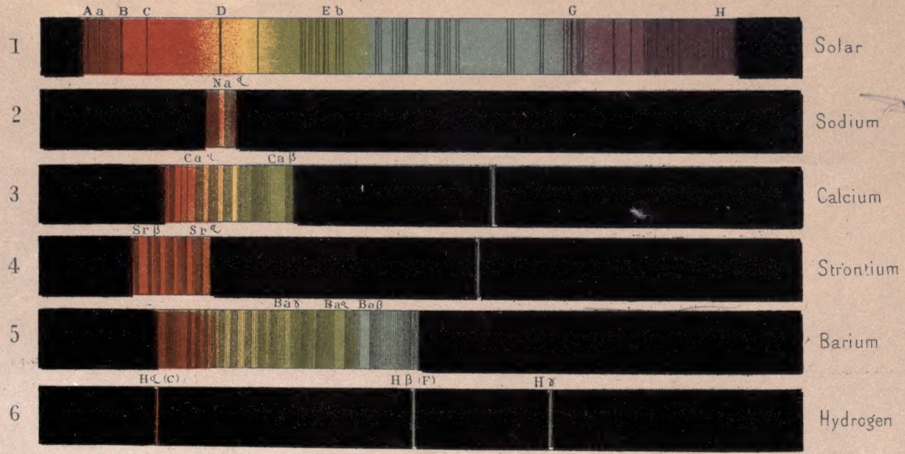

NATURAL PHILOSOPHY

FOR THE USE OF

Schools and Academies.

BY

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PREFACE.

It has been the aim of the authors to state in clear, simple, and accurate terms the elementary facts and principles of Physics as they are understood at the present time, and the most important practical applications of these principles. This book is in no sense a revision of the Natural Philosophy of the "Cambridge Course of Physics," but an entirely new and independent work, differing from the earlier work both in matter and in method of presentation.

The authors have striven to give due prominence to every department of the subject, and at the same time to bring the whole within reasonable limits. The province of Physics is now so extensive, while the time allotted to its study in our schools is usually so brief, and the tastes of teachers and the capacities of classes are so varied, that it is impossible to prepare a text-book that shall meet the requirements of all. The authors have endeavored to adapt this book to the wants of the greatest possible number by the use of two kinds of type. The fundamental facts and principles, and the simplest applications of these principles, are printed in the coarser type. It is

hoped that these portions will furnish a course in Physics brief enough for those whose time is most limited. The matter in the finer type may make the book acceptable to many teachers who have more than enough time at their disposal for the briefer course, as it will enable them to pursue any subject at greater length, according to their individual tastes, the ability of their classes, or the apparatus at their disposal. The teacher may also be able to meet the different tastes and capacities of the same class, by requiring those who are slow of apprehension and have little aptitude for Physics to master only the portion in coarse print; and inducing others, who are interested in the subject and able to cope with it, to study portions of the fine print also. It will be found that both kinds of type are very clear and legible.

The matter in coarse type is entirely independent of that in the fine type, but there is no violent dislocation between the two. The manuscript was first prepared without any reference to the parts which were to appear in different type, and the sections and paragraphs for the coarse type were selected afterwards. After the selection for coarse type had been made, only very slight alterations were found to be necessary to render these portions independent of the others.

It would be impossible to give all the sources from which the material of the text has been derived, since very much of it is presented in the form in which it has shaped itself in the mind of one of the authors during many years of daily oral teaching. Considerable material has, however, been drawn from Deschanel's Natural Philosophy, Gordon's Electricity, Loomis's Meteorology, and other

standard works. Theories have been given, as a rule, either in the words of their authors or of some recognized authority; and many facts and illustrations have been taken from the above-named and similar works with little or no alteration of expression.

The majority of the diagrams in Light and Electricity are from original drawings. All the other cuts have been copied and reduced in size by the phototype process from standard works. The majority of the cuts have been taken from Deschanel's Philosophy, Gordon's Electricity, and Loomis's Meteorology. The following list contains about all the books from which material of any kind has been drawn. These books are all invaluable to teachers and others interested in Physics.

Deschanel's Natural Philosophy. D. Appleton & Co.: New York (reprint).

Ganot's Physics. Wm. Wood & Co.: New York (reprint).

Tait's Recent Advances in Physical Science. Macmillan & Co.: New York.

Maxwell's Matter and Motion. Macmillan & Co.: New York.

Tyndall's Sound. D. Appleton & Co.: New York (reprint).

Mayer's Sound. D. Appleton & Co.: New York.

Helmholtz's Popular Lectures 1st Series. D. Appleton & Co.: New York (reprint).

Taylor's Sound and Music. Macmillan & Co.: New York.

Tyndall's Heat a Mode of Motion. D. Appleton & Co.: New York (reprint).

Maxwell's Theory of Heat. D. Appleton & Co.: New York (reprint).

Mayer's Light. D. Appleton & Co.: New York.

Tyndall's Lectures on Light. D. Appleton & Co.: New York.

Rood's Modern Chromatics. D. Appleton & Co.: New York.

Jeffries's Color Blindness. Houghton, Mifflin, & Co.: Boston.

Gordon's Electricity and Magnetism. D. Appleton & Co.: New York (reprint).

Jenkin's Electricity and Magnetism. D. Appleton & Co.: New York (reprint).
Tyndall's Lessons in Electricity. D. Appleton & Co.: New York (reprint).
Prescott's Telegraph. D. Appleton & Co.: New York.
Prescott's Telephone, etc. D. Appleton & Co.: New York.
Sawyer's Electric Lighting. D. Van Nostrand: New York.
Loomis's Meteorology. Harper & Brothers: New York.
Stewart's Energy. D. Appleton & Co.: New York.

CONTENTS.

NATURAL PHILOSOPHY.

NATURAL PHILOSOPHY.

I.

CONSTITUTION OF MATTER.

1. *Molecules and Atoms.* — It is now generally held by physicists that all bodies are made up of very small distinct particles, called *molecules*, which are in turn made up of still smaller particles, called *atoms*. These molecules are far too minute to be seen with the most powerful microscope, and are separated by spaces many times as large as the molecules themselves. It has been estimated that there are at least 300 quintillions of molecules in a single cubic inch of air, — a number which would be represented by 3 followed by twenty ciphers. At the same time it is believed that the material molecules themselves occupy only $\frac{1}{3000}$ of the space in the cubic inch. These molecules are usually made up of two or more atoms, which are probably very far apart compared with their size. We thus gain some notion of the extreme fineness of the atomic dust of which matter is composed.

It has been found possible to resolve bodies into molecules, and decompose the molecules into atoms; but it is impossible to divide the atoms by any means at our disposal.

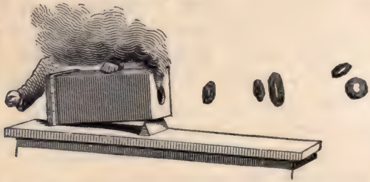
2. *Substance.* — The substance of a body depends upon the internal structure of its molecules. All the molecules

of the same substance are supposed to be exactly alike. A body may be divided and subdivided at will, and the substance of every portion remain the same so long as the molecules remain intact. The moment the molecules are divided, or their structure altered by changing the kind, number, or grouping of their atoms, the substance of the body is changed.

3. *The Ether.* — The atoms and molecules of a body are supposed to be suspended in a highly rarefied and elastic fluid, which fills the entire universe and permeates all bodies. This fluid is called the *ether.* It fills alike the spaces among the atoms and molecules of bodies, and among the planets and stars of the universe. It is without weight, and portions of its mass may move about in it without the slightest friction.

4. *Theory of Vortex Atoms.* — Take a box having a round hole in front and a piece of stretched cloth for its back.

Fig. 1.



Sprinkle a little ammonia on the bottom of the box, and place in it a small dish of muriatic acid, so as to fill the box with the fumes of sal-ammoniac. On striking the back of the box a sudden blow, a ring of smoke will issue from the opening, similar to those which are sometimes seen to escape from the smoke-stack of a locomotive. The box and rings are shown in Figure 1.

The rings will move through the atmosphere as if they were solid bodies. When two of these come into collision they are thrown into energetic vibration. If two happen to be moving in the same direction, with their centres on the same line, and

their faces perpendicular to this line, the one in front expands and goes slower, and the one behind contracts and goes faster, till it overtakes and passes through the one in front; it will then begin to expand, and to move slower, and allow the other one to pass through it in turn; and so on alternately. In all these changes of form each ring preserves its individuality. Each ring, as it floats through the atmosphere, is all the time made up of precisely the same particles of air and smoke, and these are precisely the same particles of air and smoke that were driven out of the box by the blow on its back. It is not merely particles of sal-ammoniac which are moving through the air, but a portion of the air has become, as it were, a different substance from the surrounding air, through which it moves very much like a solid body. If we attempt to cut one of these rings, it either recedes from the knife or wriggles around it, so as to escape without injury.

Every portion of the ring is continually rolling round on its circular core. The particles on the inside of the ring are moving forward, and those on the outside are moving backward, as shown by the arrows in Figure 2. Such rings are called *vortex rings*.

Fig. 2.

Helmholtz has shown by mathematical investigation, that, were such vortex rings once started in a perfect fluid, such as the ether is assumed to be, they would always retain their individual character, and would be absolutely indestructible except by the power which created them. No process at our disposal could either start such a vortex ring in the ether, or destroy one which was already in existence. These vortex rings might be either circular in form or have any conceivable number of knots and windings upon them.

According to Sir William Thompson, the atoms of ordinary matter are simply minute vortex rings in the ether. The ether is a perfect fluid, which fills the entire universe, and what we call matter is simply portions of this ether animated with vortex motion. The atoms of the same substance are alike, because the vortex rings are all alike in form and character. The atoms

of different substances differ, because the vortex rings have different forms and characteristics.

5. *The Atomic and Molecular Structure of Bodies analogous to the Molar Structure of the Sidereal Universe.* — The Sidereal Universe is composed of stars, each of which is probably, like our own sun, the centre of a solar system composed of sun and planets. The planets and moons which compose a solar system correspond to the atoms which compose the molecules, and the solar systems correspond to the molecules which compose the body. The planets in the solar system are sometimes found singly, as in the case of Venus, and sometimes in groups, as in the case of Jupiter. The same is true of the atoms in the molecules.

6. *All Matter is Porous.* — From the account just given of the structure of matter, it will be seen that all matter is *porous*, that is, filled with spaces which are not occupied by material particles. When these pores are too small to be seen with the microscope, they are called *physical* pores. In many cases the pores of bodies are large enough to be seen. This is the case with wood and many other substances. Such pores are called *sensible* pores.

7. *Atomic, Molecular, and Molar Motion.* — Every particle of matter in the universe is in incessant motion. The atoms are all the time moving about in the molecules ; the molecules, in bodies ; and bodies, in space. The motion of the atoms within the molecules is called *atomic* motion ; that of the molecules in bodies, *molecular* motion ; and that of bodies in space, *molar* motion. Molar motion is often called *mechanical* motion. Sometimes the term *molecular* is applied to the motion of both atoms and molecules.

8. *The Three Great Forces of Nature.* — There are three forces corresponding to the three orders of material units. These are *affinity*, *cohesion*, and *gravity*.

Affinity is the force which binds together the atoms into the molecules. It is therefore an *atomic* force. It is the strongest of the forces, but it acts only through infinitesimal distances.

Cohesion is a *molecular* force. It binds together the molecules into bodies. It is a weaker force than affinity, but is capable of acting through greater, though still insensible distances.

Gravity is a *molar* force. It binds together bodies. It is the weakest of the three forces, but is capable of acting through all known distances.

Though cohesion binds together molecules, and gravity bodies, each probably does so by acting directly upon the ultimate atoms of which matter is composed.

9. *Elasticity.* — Elasticity is the tendency of a body to spring back to its original condition when it has been distorted in any way. Any distortion whatever, whether produced by stretching, by bending, by twisting, by compression, or by rarefaction, is called a *strain.* The force which produces the strain is called a *stress.* Elasticity is always developed by some kind of strain. It is called elasticity of *traction*, of *flexure*, of *torsion*, or of *compression*, according to the kind of strain by which it is developed. All bodies are elastic to some extent, but usually, when the distortion proceeds beyond a certain point, the elasticity of the body breaks down. The point of strain at which the elasticity breaks down is called the *limit* of the elasticity of the body.

10. *The Three Orders of Material Units.* — The three orders of material units are *atoms*, *molecules*, and *bodies.*

11. *Chemical Properties of Matter.* — The properties of matter which grow out of the atomic structure of the molecules and the action of affinity are called *chemical properties.*

12. *Physical Properties of Matter.* — The properties of

matter which grow out of the molecular structure of bodies and the action of cohesion are called *physical properties*.

13. *The Physical Sciences.* — The *physical sciences* deal with the action of forces on material units, irrespective of the phenomena of life.

Mechanics deals with the action of forces and the laws of motion, irrespective of any order of material units.

Astronomy deals with gravity and molar units.

Physics deals with cohesion, molecules, and physical properties of matter.

Chemistry deals with affinity, atoms, and chemical properties of matter.

Natural Philosophy includes both Mechanics and Physics. In any treatise on the various branches of Physical Science, it is impossible to draw any sharp line of demarcation between them.

II.

MECHANICS.

A. Definitions. — Units. — Newton's Laws of Motion.

14. *The Three Fundamental Units.* — The three *fundamental* units of Mechanics, from which all the other mechanical and physical units are derived, are the *unit of time*, the *unit of length*, and the *unit of mass*.

In the English system these units are the *second*, the *foot*, and the *pound* avoirdupois. In the French system they are the *second*, the *centimetre*, and the *gramme*.

15. *English and French Units of Length.* — The English standard unit of length is the *yard*, which is divided into three equal parts, called *feet*. The foot is subdivided into twelve equal parts, called *inches*. The yard is simply the length marked on a certain rod preserved by the government.

The French standard unit of length is the *metre*. This is, theoretically, the forty-millionth of the earth's meridian. Practically, it is the length of a rod preserved by the French government, which differs appreciably from the theoretical length of the metre. The metre is about $3\frac{1}{4}$ feet. The metre is divided into ten, one hundred, and one thousand equal parts, called *decimetres*, *centimetres*, and *millimetres*. *Decametre*, *hectometre*, and *kilometre* are, respectively, ten metres, one hundred metres, and one thousand metres. In the French system of units the prefixes *deci*, *centi*, and *milli* always indicate tenths, hundredths, and

thousandths of the unit, while the prefixes *deca*, *hecto*, and *kilo* always indicate tens, hundreds, and thousands of the units. The decimal division of the units, and the natural relations of the units of different kinds, render the French, or *Metric*, system of units the most convenient system ever devised.

For the purpose of readily comparing the French units of length with our familiar English units, it will be convenient to remember that a metre is about forty inches; a decimetre, about four inches; a centimetre, about $\frac{4}{10}$ of an inch; and a millimetre, about $\frac{1}{25}$ of an inch. A kilometre is about five furlongs, or $\frac{5}{8}$ of a mile.

16. *Units of Surface and of Volume.* — The units of surface are squares, one of whose sides is the unit of length. Thus, the English units of surface are the *square yard*, the *square foot*, and the *square inch*. The French units of surface are the *square metre*, the *square decimetre*, and the *square centimetre.*

The units of volume are cubes, one of whose edges is the unit of length. The English units of volume are the *cubic yard*, the *cubic foot*, and the *cubic inch*. The French units of volume are the *cubic metre*, the *cubic decimetre*, and the *cubic centimetre.* The French unit of capacity is the *cubic decimetre.* It is called the *litre*, and is equal to about $1\frac{3}{4}$ pints.

17. *Units of Mass.* — The *mass* of a body is the quantity of matter which it contains. The English unit of mass is the mass of a certain piece of metal preserved by the government and called the *pound avoirdupois*. It is divided into 7000 equal parts, called *grains*. The French unit of mass is the mass of a cubic centimetre of water at its maximum density. It is called a *gramme*, and is equal to about $15\frac{1}{2}$ grains. A kilogramme is equal to about $2\frac{1}{5}$ pounds.

18. *Unit of Density.* — The *density* of a body is the quan-

tity of matter in a unit of its volume. The density of water at a temperature of 39° F. is usually taken as the unit of density.

19. *Units of Velocity.* — *Velocity* is rate of motion. The English unit of velocity is the velocity of one *foot a second.* The French unit is the velocity of a *centimetre a second.*

When we speak of the velocity of a body as being five, ten, or twenty feet a second, we mean that, at the instant to which we refer, the body is moving fast enough to go five, ten, or twenty feet in a second, provided it were to keep on moving at the same rate. It does not, however, follow that it will actually go five, ten, or twenty feet in a second, for its rate may change.

20. *Different Aspects of the Action of Forces on Matter.* — Any push or pull, of whatever origin, upon any portion of matter is called a *force.* In the realm of matter these forces always act *between* two different portions of matter. Thus, affinity is a pull between two atoms; cohesion, a pull between two molecules; and gravity, a pull between two bodies. The action of a pulling, or *attractive*, force may be illustrated by fastening two balls to the ends of an india-rubber cord and then separating the balls so as to stretch the cord. The stretched cord will pull upon both balls. The action of a pushing, or *repulsive*, force may be illustrated by placing a rod of india-rubber between two balls and then crowding the balls together. The compressed rubber will push upon both balls.

This action of a force between two portions of matter takes different names according to the aspect under which it is viewed. When we take into account the whole phenomenon of the action between the two portions of matter, we call it a *stress*. This stress, according to the mode in which it acts, may be described as *attraction*, *repulsion*, *tension*, *pressure*, *torsion*, etc. When we confine our attention to one of the portions of matter, we see only one aspect of

the stress, namely, that which affects the portion of matter under consideration. This aspect of the phenomenon we call, with reference to its *effect*, an *external force*, acting upon that portion of matter, and, with reference to its *cause*, the *action* of the other portion of matter. The opposite aspect of the stress is called the *reaction* on the other portion of matter.

21. *Newton's First Law of Motion.—Every body perseveres in its state of rest or of moving uniformly in a straight line, unless compelled to change this state by external forces.* This is Newton's first law of motion. No portion of matter in the universe, so far as known, is absolutely at rest. Were there such a portion of matter, it could be put in motion only by an external force. Bodies are commonly spoken of as at rest when they are not changing their positions with respect to other bodies around them. Thus, we say that a body is at rest on the deck of a steamer, though it is really moving forward with the steamer; and that bodies are at rest on the surface of the earth, though they are moving along with the earth. In all such cases bodies are only relatively at rest. In common language bodies are said to be at rest with respect to each other when they are all moving along at the same rate and in the same direction. When, in common language, a body is said to be put in motion, what really takes place is that its motion is changed either in rate or direction.

Unless acted upon by external forces, a moving body would always go on in a straight line and at a uniform rate. This seems to be contradicted by common experience. All moving bodies at the surface of the earth show a decided tendency to stop. But all such moving bodies are acted upon by some external force acting as a resistance. The chief resistances encountered by moving bodies are friction and resistance of the atmosphere. In proportion as these resistances are diminished, the longer is the time a body

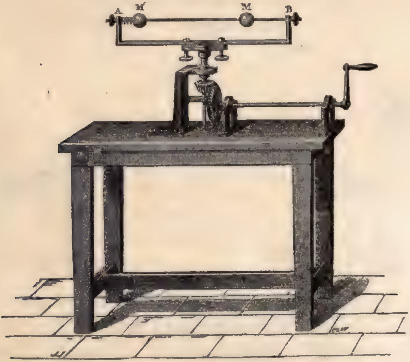
will continue to move. A smooth stone is soon brought to rest when sliding over the surface of the earth. The same stone will slide much longer over the smooth surface of ice, where there is less friction. A heavy metallic top in rapid rotation will spin for twenty minutes in the air. The same top will spin over an hour in a vacuum. Since the time a body will continue in motion increases in proportion as the resistance is diminished, we may reasonably infer that, were the resistance entirely removed, the body would continue in motion forever. To keep bodies in motion at the surface of the earth, it is necessary to bring some external force to bear on them sufficient to balance the resistance which they encounter. There will be no change in the motion of a body when acted upon by external forces, provided these forces balance one another, or are in a state of equilibrium.

Fig. 3.

22. *Inertia.* — The tendency of a body to persevere in its state of rest or motion is called *inertia.* The inertia of a body is directly proportional to its mass. This inertia must be overcome by some external force in order to put a body in motion, or to change the rate or direction of its motion. It takes *time* for a force to overcome the inertia of matter. Hence, when a body receives a sudden blow, the part of the body immediately receiving the blow yields before there is time to overcome the inertia of the surrounding parts.

There are many striking illustrations of inertia. If a number of checkers are piled up in a vertical column, one of them may be knocked out by a very rapid blow with a table knife without overturning the column. A feeble blow will fail. Stick two needles into the ends of a broomstick and rest the needles on two glass goblets, as shown in Figure 3. Strike the middle of the stick a quick, sharp blow with a heavy poker. The stick will break without breaking the needles or the goblets. Here again a feeble or indecisive blow will fail. A soft body, fired fast enough, will hit as hard as lead. A tallow candle may be fired from a gun through a pine board.

Fig. 4.



23. *Centrifugal Force.*—The so-called *centrifugal force* is an illustration of Newton's first law of motion. It is simply the tendency of the parts of a rotating body to keep moving in straight lines. This tendency increases with the speed of rotation. When a body is rotating very rapidly, the tendency of the parts to move in straight lines is suffi-

cient to overcome the cohesion of the body. In this case the body will fly in pieces. If a stone be fastened to the end of a string and twirled rapidly around the finger, the tendency of the stone to fly off in a straight line may become sufficient to break the string. In this case the stone will start off in a line tangent to the circle it was describing at the point where the stone happened to be.

This tendency to move on in a straight line must be counteracted by the force acting towards the centre, in order to keep a body moving in a circle. The faster the body moves, the greater the pull needed to keep the body in its circular path. The greater the pull *upon* the body towards the centre, the greater the pull *of* the body away from the centre. The pull upon the body towards the centre is called the *centripetal force*, and the pull of the body away from the centre is called the *centrifugal force*. These two forces are only the two aspects of the stress of attraction between the body and the centre about which it is revolving.

Fig. 5.

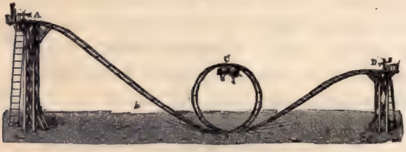
The pull of a revolving body away from the centre may be illustrated by the pieces of apparatus shown in Figures 4 and 5. In the first, two balls M and M' are placed on the rod $A\ B$, which passes through them. The rod is then put in rapid rotation by turning the crank at the end of the table. The balls fly apart.

If the flexible rings of Figure 5 are mounted on the whirling table in place of the rod, and put in rapid rotation, they will become more and more flattened as the speed of rotation increases. This change of form is due

to the pull of each part of the rings away from the central axis. The pull will be greatest at the central point of the rings, because this part is moving at the highest speed. It was in this way that the earth became flattened at the poles while in the fluid state.

The *centrifugal railway* (Figure 6) shows a curious effect of this outward pull. A carriage starting from *A* descends the incline to *B*, passes up around the circle *C*, and then up the incline to *D*. The outward pull of the carriage due to its velocity is sufficient to keep it against the rails while passing around the circle, though it is part of the time travelling bottom up.

Fig. 6.



24. *Stability of a Rotating Body.* — The tendency of the particles of matter to keep moving in the same plane explains why a top will stand upright so long as it is spinning rapidly, though it topples over at once as soon as it comes to rest. For the same reason a bicycle is not easily overturned while its large wheel is in rapid rotation.

25. *External Forces tend to put Bodies in Motion or to change their Velocities.* — Suppose a rubber cord fastened at one end to a body, not acted on by any other force than the tension of the cord, and suppose the cord to be kept stretched to the same extent all of the time, so as to exert a uniform pull upon the body. The body will begin to move in the direction of the pull, and will move faster and faster the longer the pull continues. The body will gain the same amount of velocity each second. If it were moving at the

rate of two feet a second at the end of the first second, it will be moving at the rate of four feet a second at the end of the second second, at the rate of six feet a second at the end of the third second, and so on.

26. *Units of Force.* — Forces may be measured either by the pressure which they would produce or by the rate at which they would increase the velocity of a mass of matter.

In the former case the unit of force is the force of gravity on a unit of mass. In the English system it is the force of gravity on a mass of a pound or a grain, and is called a *pound* or a *grain*. In the French system it is the force of gravity on a mass of a gramme, and is called a *gramme*. These units are called *gravitation* units; and since they depend upon the intensity of gravity, they are *variable*, changing with the intensity of gravity at different places on the surface of the earth, and at different elevations above the surface.

In the latter case the unit of force is the force that will impart to a unit of mass a unit of velocity in a unit of time. In the English system it is the force that will impart to a mass of a pound a velocity of a foot in a second. It is called a *poundal*. At Greenwich it takes 32.2 poundals of force to hold up a pound.

A system of absolute measurement has been devised in England, and adopted by the British Association. The units of this system are all based upon the centimetre, gramme, and second, as the three fundamental units of length, mass, and time. This system of measurement is called the *centimetre-gramme-second system*, or more briefly, the *C. G. S. system*. Its units are called the *centimetre-gramme-second units*, or more briefly, the *C. G. S. units*.

In the *C. G. S.* system the unit of force is the force that will impart to a mass of a gramme a velocity of one centimetre a second. It is called a *dyne*. It takes 445,000 dynes of

force to hold up a pound at Greenwich. These units are independent of gravity, and are *invariable.* They are called *absolute units.*

27. *The Impulse of Force.* — The effect of a force in producing motion is directly proportional to its intensity and the time during which it acts. The product of the intensity of a force and the time during which it acts is called the *impulse* of the force.

28. *Momentum.* — The motion of a body is measured by the mass and the velocity of the body, and is directly proportional to the two. If two bodies have equal velocities, but one of them has five times the mass of the other, it is said to have five times the motion. Or, if two bodies have equal masses, and one of them has five times the velocity of the other, it is said to have five times the motion of the other. The product of the mass of a body and its velocity is called the *momentum* of the body.

29. *Newton's Second Law of Motion.* — *Change of motion is proportional to the impressed force, and takes place in the direction in which the force acts.* This is Newton's second law of motion.

By motion, as here used, Newton means what is now called *momentum*, in which the *quantity of matter* moved is taken into account as well as the *rate* at which it travels. For instance, there would be the same change of motion whether the velocity of four pounds was changed one foot a second or the velocity of one pound four feet a second. In either case the change of momentum would be four.

By impressed force Newton means what is now called *impulse*, in which the *time* the force acts is taken into account as well as the *intensity* of the force. Thus, the impulse, or impressed force, would be the same whether a force of a poundal were acting five seconds or a force of five poundals was acting one second. In either case the impulse, or impressed force, would be five.

Newton's second law, stated in terms of momentum, would be: *The change of momentum of a body is numerically equal to the impulse which produced it, and is in the same direction.*

An unbalanced external force acting upon a body always changes the velocity of the body in the direction in which it acts. This change of velocity is called *acceleration.* The acceleration produced in a given time by a force acting upon a body is precisely the same whether the body is at first at rest or in motion, or whether the force is acting alone or with other forces.

Imagine a platform, and upon it a little iron ball, and 5 feet from the ball a magnet strong enough to pull the ball 3 feet towards itself in a second, and to give it a velocity of 6 feet in the same time. Imagine the ball, magnet, and platform placed within a car, which is at first standing still. Suppose the magnet placed on the platform 5 feet from the ball in any direction whatever, it will draw the ball 3 feet towards itself in a second, and give it an acceleration of 6 feet in the direction of the pull. Now suppose the car moving forward at the uniform rate of 12 feet a second. The ball will of course be moving forward at the same rate. If now the magnet is placed on the platform 5 feet from the ball, as before, it will draw the ball 3 feet towards itself, and give it an acceleration of 6 feet a second in the direction of the pull, as before. If the magnet is placed in front of the ball, the acceleration of 6 feet will be in the direction of the original motion of the ball, and the forward velocity of the ball at the end of the second will be $12 + 6 = 18$ feet a second. If the magnet is placed behind the ball, the acceleration of 6 feet will be in the opposite direction to the original motion, and the forward velocity of the ball at the end of the second will be $12 - 6 = 6$ feet a second. If the magnet is placed at the side of the ball, the acceleration will be to the right or left of the direction of the original motion of the ball, and at the end of the second the ball will have a forward velocity of 12 feet a second, and a lateral velocity in the direction of the pull of the magnet of 6 feet a second.

When the acceleration is opposed to the original motion of a body, it is usually called a *retardation*.

Imagine the platform with the ball and magnet on it dropped over a precipice. The ball will then be acted upon by two forces, both of which will give it an acceleration. Gravity will draw it 16 feet towards the earth, and give it an acceleration of 32 feet in that direction in a second, and the magnet will draw it 3 feet towards itself, and give it an acceleration of 6 feet in this direction in a second. Each force has drawn the ball the same distance, and given it the same acceleration in the direction in which it acts as it would have done had it acted alone.

Newton's second law, stated in terms of acceleration, would be: *When any number of forces act upon a body, the acceleration due to each force is the same in magnitude and direction as if the others had not been in action.*

The total acceleration produced by the action of a force is directly proportional to the impulse of the force, and inversely proportional to the mass acted upon. A force of 40 poundals acting for 20 seconds upon a mass of 50 pounds would produce an acceleration of $\overline{40 \times 20} \div 50 = 16$ feet. A force of 300 dynes acting 80 seconds upon 200 grammes would produce an acceleration of $\overline{300 \times 80} \div 200 = 120$ centimetres.

The total change of momentum produced by the action of a force is numerically equal to the impulse of the force. A force of 40 poundals acting 30 seconds would produce a change of momentum equal to $40 \times 30 = 1200$ units (English). A force of 250 dynes acting 20 seconds would produce a change of momentum equal to $250 \times 20 = 5000$ units (C. G. S.).

QUESTIONS ON NEWTON'S SECOND LAW.

1. What acceleration would be produced by a force of 30 poundals acting on a mass of 80 pounds for 70 seconds?

2. What acceleration would be produced by a force of 96 poundals acting upon a mass of 36 pounds for 500 seconds?

3. What acceleration would be produced by the action of a force of 720 dynes on a mass of 300 grammes for 40 seconds?

4. What acceleration would be produced by a force of 240 dynes acting on a mass of 3 kilogrammes for 3 minutes?

5. What must be the intensity of a force that would give 90 pounds an acceleration of 1000 feet in 20 seconds?

6. What must be the intensity of a force that would give a mass of 80 grammes an acceleration of 50 metres in 2 minutes?

7. What must be the mass of a body to which a force of 60 poundals would give an acceleration of 500 feet in 30 seconds?

8. What must be the mass of a body to which a force of 500 dynes would give an acceleration of 8 decimetres in 8 seconds?

9. What momentum would be imparted to a body by a force of 70 poundals in 90 seconds?

10. What momentum would be imparted to a body by a force of 350 dynes in 75 seconds?

11. What force would be needed to change the momentum of a body 300 units (English) in 9 seconds?

12. What force would be needed to change the momentum of a body 900 units (C. G. S.) in 60 seconds?

13. How long will it take a force of 120 poundals to impart a momentum of 700 units to a body?

14. How long would it take a force of 600 dynes to impart a momentum of 19,000 units to a body?

15. How long would it take a force of 20 poundals, acting in the opposite direction to the motion of the body, to stop a body having a momentum of 300 units?

16. How long would it take a force of 80 dynes, acting in the opposite direction to the motion of the body, to stop a body having 1,000 units of momentum?

17. How long would it take a force of a poundal, acting in the opposite direction to the motion of the body, to stop a body having a momentum of 960 units?

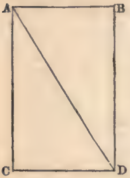
18. How long would it take a force of a dyne, acting in the opposite direction to the motion of the body, to stop a body having a momentum of 572 units?

19. How long would it take a force of 40 poundals, acting in the opposite direction to the motion of the body, to stop a mass of 50 pounds having a velocity of 80 feet a second?

20. How long would it take 300 dynes of force, acting in the opposite direction to the motion of the body, to stop a mass of 90 grammes with a velocity of 600 centimetres a second?

30. *Parallelogram of Motion.*—To find the path of a body *A* (Figure 7) acted on by two forces at the same time,

Fig. 7.



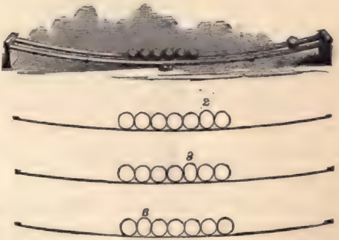
draw *A B* to represent the path the body would have taken had it been acted on by the first force alone, and *A C* to represent the path it would have taken had it been acted on by the other force alone. Through *B* draw *B D* parallel to *A C*, and through *C* draw *C D* parallel to *A B*, so as to complete the parallelogram *A B D C*. Draw the diagonal *A D*. This diagonal will represent the path taken by the body when acted upon by both forces together.

31. *Newton's Third Law of Motion.*—Newton's third law of motion is as follows: *Reaction is always equal and opposite to action; that is to say, the actions of two bodies upon each other are always equal and in opposite directions.*

This law simply states the fact that a force always acts upon two portions of matter, and that the stress, whether that of tension or pressure, is equal upon both portions. A stone raised from the earth attracts the earth just as much as the earth attracts the stone. Gravity really acts as a stress of tension between the two, and pulls them equally but in opposite directions. When the stone falls the earth moves up to meet it. When the two meet they have each the same momentum, but the earth, owing to its great mass, has only a very small velocity. When a cannon is fired, the ignited powder pushes back upon the cannon just as hard as it pushes forward on the ball. Were the cannon as free to move as the ball, it would start back, or *recoil*, with the same momentum that the ball starts forward with, but of course with a less velocity.

32. *Collision of Elastic Bodies.* — We have an illustration of action and reaction in the collision of elastic bodies. Place two ivory balls of exactly the same size at the centre of the curved railway (Figure 8). Move one of the balls up the railway on one side, and let it roll back against the one at rest. There will be a slight strain of compression when the balls strike, and this will develop a stress of elasticity between the balls which will act equally upon them and in opposite directions. This stress will stop the first ball, and start the second off with the velocity the first had on striking it.

Fig. 8.



Place several ivory balls of the same size on the centre of the track (Figure 8), and allow the first ball to roll against the end of the line. • All the balls will remain at rest except the last, which will be shot up the track. In this case the strain of compression and stress of elasticity have been propagated along the line from ball to ball. Each ball has been compressed a little in turn, and in recovering itself has pushed upon the ball behind it enough to stop it, and upon the one in front enough to flatten it a little. Each ball was kept from moving forward by the reaction of the ball in front, except the last.

B. Work and Energy.

33. *Work.* — *Work* is said to be done when anything is moved against resistance. We may consider work either with reference to the force that moves the body or with

reference to the resistance overcome. When we think of the force as moving the body, we say that work is done by the *force* upon the body. When we think of the resistance as overcome by the body, we say that work is done by the *body* upon the resistance. When we think of the resistance as impeding the motion of the body, we say that work is done by the *resistance* upon the body. These terms apply to different aspects of the same work. Thus, when we raise a weight, in winding up a clock, we may say that work is done by the *force* used upon the weight, or by the *weight* upon or against gravity, or by *gravity* upon the weight. The amount of work done is the same, in whatever aspect we view it. When the clock weight runs down again, we may say that work is done by *gravity* upon the weight, or by the *weight* upon the resistance of the wheels, or by the *resistance of the wheels* upon the weight, according to the aspect in which we view the work. When a weight is allowed to fall freely to the earth, the work done is that of increasing the velocity of the body. In this case work is done by gravity *upon* the body, and *by* the body upon its inertia.

Work is done in every case in which the velocity of a body is changed, for the inertia of the body always resists this change.

34. *Units of Work.* — The unit of work is the work done in moving anything a unit of distance against a unit of resistance, or by a unit of force acting through a unit of distance. A resistance is, of course, merely the opposing action of some force, and is measured in poundals or dynes. The English unit of work is the work done in moving a mass one foot against a poundal of resistance, or by a force of a poundal acting one foot. It is called a *foot-poundal.* The C. G. S. unit of work is the work done in moving a mass one centimetre against a dyne of resistance, or by the force of a dyne acting one centimetre. It

is called an *erg*. There are 421,393.8 ergs in a foot-poundal. These are *absolute* units.

The gravitation unit of work is the work done in raising a unit of mass a unit in height. The English unit of work is the work done in raising a pound one foot high. It is called a foot-pound. It varies with the force of gravity in different parts of the earth and at different elevations. At Greenwich there are 32.2 foot-poundals in a foot-pound.

35. *The Amount of Work done in stopping a Moving Body.* — If we let M represent the number of units of mass in a body, and V the number of units in its velocity, then $M V$ will represent its *momentum*. This is the usual formula for momentum.

Now it will take a unit force acting against the motion of a body $M V$ seconds to stop the body, for the force would diminish the momentum of the body one unit each second, and the body has $M V$ units of momentum. Suppose the body has 7 units of mass and 8 units of velocity, it will have 56 units of momentum, and it will take a unit force 56 seconds to stop the body.

As the force is acting against the motion of the body, its velocity will be uniformly diminished till it becomes zero. The mean velocity during the time the force is acting is therefore $\frac{1}{2}$ of the velocity it had at first, and the distance the body goes will be equal to the product of the time and the mean velocity. In the example above, the mean velocity is $8 \div 2 = 4$, and the distance is $56 \times 4 = 224$ feet.

In the general case, the time it would take a unit force to stop the body is $M V$ seconds, the mean velocity during the time is $\frac{1}{2} V$, and the distance through which the force must act to stop the body is $M V \times \frac{1}{2} V = \frac{1}{2} M V^2$. In other words, the distance a unit force must act to stop a moving body is equal to the product of the momentum of the body and $\frac{1}{2}$ of its velocity. From the definition of a unit of work, it will be seen that this is the number of units of work done in stopping the body.

36. *The Amount of Work done in imparting to a Body any Acceleration.* — The time it will take a unit force to impart an

acceleration v will be equal to the number of units of momentum imparted to the body. Suppose the mass of the body is 5 and the acceleration imparted to it is 8 feet a second; the momentum imparted to the body will be $5 \times 8 = 40$ units. It would take a unit force 40 seconds to impart this momentum. The work done in imparting this momentum is precisely the same whether the body were originally at rest or in motion. Suppose the body originally at rest. The mean velocity during 40 seconds would be $8 \div 2 = 4$; and the distance the force would have to act to impart the acceleration would be equal to the space passed over by the body, or $40 \times 4 = 160$. It would therefore require 160 units of work to impart to a mass of 5 pounds an acceleration of 8 feet a second. In general, the work done in producing any acceleration or retardation is equal to the product of the change of momentum and ½ the acceleration or retardation. Let $m v$ represent the change of momentum, and v represent the acceleration or retardation. Then the work done in producing the acceleration or retardation will be equal to $\frac{1}{2} m v^2$.

QUESTIONS ON WORK.

21. How long would it take a poundal of force to stop a mass of 50 pounds moving at the rate of 80 feet a second?

22. How long would it take a dyne of force to stop a mass of 200 grammes moving at the rate of 800 centimetres a second?

23. How long would it take a force of 15 poundals to stop a mass of 500 pounds moving with a velocity of 90 feet a second?

24. How long would it take a force of 500 dynes to stop a mass of 900 grammes moving with a velocity of 600 centimetres a second?

25. Through what distance would a poundal of force have to act to stop a mass of 30 pounds moving with a velocity of 70 feet a second?

26. Through what distance would a dyne of force have to act to stop a mass of 280 grammes moving with a velocity of 700 centimetres a second?

27. Through what distance would a force of 20 poundals have to act to stop a mass of 250 pounds moving with a velocity of 60 feet a second?

28. Through what distance would a force of 75 dynes have to act to stop a mass of 80 grammes moving with a velocity of 1200 centimetres a second ?

29. How many foot-poundals of work would be done in stopping a mass of 90 pounds moving with a velocity of 500 feet a second ?

30. How many ergs of work would be done in stopping a mass of 600 grammes moving with a velocity of 200 centimetres a second ?

31. How far would a poundal of force have to act to impart to a mass of 80 pounds an acceleration of 40 feet a second ?

32. How far would a dyne of force have to act to impart to a mass of 800 grammes an acceleration of 300 centimetres a second ?

33. How many foot-poundals of work would be done by a force in imparting to a mass of 400 pounds an acceleration of 20 feet a second ?

34. How many ergs of work would be done by a force in imparting to a mass of 90 grammes an acceleration of 700 centimetres a second ?

35. How many foot-poundals of work must be done by a resistance to retard the velocity of a mass of 75 pounds 200 feet a second

36. How many ergs of work must be done by a resistance to retard the velocity of a mass of 1500 grammes 900 centimetres a second ?

37. *Energy.* — *Energy* is the capacity for doing work. It is measured in the same units as work, a unit of energy being the capacity for doing a unit of work. Thus, we may speak of so many foot-poundals, or of so many ergs, of energy.

The force that tends to stop a moving body acts upon it as a resistance, and, as we have seen, every moving body has the power to overcome this resistance through a greater or less distance according to its momentum and velocity. Hence every moving body has a capacity for doing work, or *energy*. A body which is not in motion

may have a capacity for doing work growing out of its condition with respect to some force. Thus, a raised weight has the ability to drive a clock, compressed steam the ability to drive a locomotive, and a coiled spring to drive a watch.

38. *Position of Advantage.* — A body is said to have a *position of advantage* with respect to a force when it is so situated that it is possible for that force to put it in motion. A weight raised from the earth has a position of advantage with respect to gravity, since it is possible for gravity to put it in motion by pulling it to the earth again. For a similar reason molecules when separated from each other have positions of advantage with respect to cohesion ; and atoms when separated from each other, with respect to affinity. A strained body has a position of advantage with respect to elasticity.

39. *Kinetic Energy.* — The energy of motion is called *kinetic energy.*

The kinetic energy of a body is equal to the product of the momentum of the body and ½ its velocity; that is, the kinetic energy of a body equals $M\ V \times \frac{1}{2}\ V = \frac{1}{2}\ M\ V^2$. For we have seen that this represents the work that must be done by a force to stop a body. Now we may regard this work either as work done *by* the force acting as a resistance *upon* the body or *by* the body *upon* the resistance.

40. *Potential Energy.* — The energy of position is called *potential energy.* It is universally true that a body, in returning from a position of advantage to its original position, does exactly the same amount of work that was done upon it in putting it in its position of advantage. Thus, to raise a pound weight 12 feet high required 12 foot-pounds of work. The same weight in falling 12 feet will do 12 foot-pounds of work. If it take 300 ergs of work to coil a spring, the spring in uncoiling will do 300 ergs of work. Hence the potential energy of a body is equal

to the work required to put the body in its position of advantage.

QUESTIONS ON ENERGY.

37. How many foot-poundals of energy has a mass of 2500 pounds with a velocity of 5000 feet a second?

38. How many ergs of energy has a mass of 8965 grammes with a velocity of 8000 centimetres a second?

39. How many foot-poundals of energy has a mass of 3 tons with a velocity of 500 feet a second?

40. How many ergs of energy has a mass of 9 kilogrammes with a velocity of 8 metres a second?

C. Composition and Resolution of Forces.

41. *Representation of Forces by Lines.* — A force may be completely represented by a line; the *length* of the line representing the *intensity* of the force, the *direction* of the line the *direction* in which the force acts, and one *end* of the line the *point of application* of the force.

42. *Resultant and Component Forces.* — There is usually some one force that would have the same effect upon a body, in producing pressure or motion, as that of the several forces that may be acting together upon it. This force is called the *resultant* of these forces, and they are called its *components*.

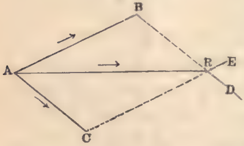
43. *Composition and Resolution of Forces.* — The combining of several forces into one resultant is called the *composition of forces;* and the decomposition of one force into two or more components, the *resolution of forces.* In the composition and resolution of forces it is necessary to find the intensity, the direction, and the point of application of the resultant or components.

44. *The Composition of Forces acting along the Same Line upon a Point.* — When several forces act in the same direction along a line on a point, their resultant would have the intensity of the sum of its components, the direction of each component, and the same point of application as the components.

When some of the forces are acting on the point in one direction and others in the opposite direction, the intensity of the resultant will be equal to the difference between the sums of the intensities of the two sets of forces, the direction of the resultant will be the direction of the larger set of components, and the point of application will be the same as that of its components.

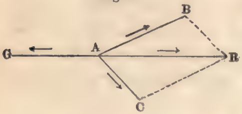
45. *Composition of two Oblique Forces acting upon a Point.* — Let two oblique forces $A\ B$ and $A\ C$ (Figure 9) be acting upon the point A in the direction indicated by the arrows. Through B draw the line $B\ D$ parallel to $A\ C$; and through C, the line $C\ E$ parallel to $A\ B$, so as to form the parallelogram $A\ B\ R\ C$. The diagonal $A\ R$ of this parallelogram will be the resultant of these two forces. The above method is called that of the *parallelogram of forces*.

Fig. 9.



If a force $A\ G$ (Figure 10), having the intensity of the resultant $A\ R$, but the opposite direction, were applied to A, it would balance this resultant, and, therefore, its components $A\ B$ and $A\ C$.

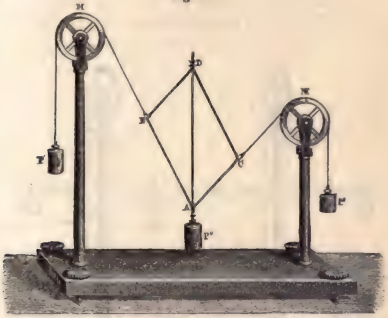
Fig. 10.



The fact that the resultant of forces may be balanced by an equal force applied to the same point in the opposite direction enables us to find the resultant of forces experimentally, and so to verify the above method. The apparatus for this experimental determination is shown in Figure 11. $A\ B\ D\ C$ is a parallelogram jointed at its four corners. Cords pass from the corners B and C over the pulleys M and N. Weights P and P' are attached to the ends of these cords. The number of ounces in the weight P is equal to the number of inches in the side $A\ B$; and the number of ounces in P', to the number of inches in $A\ C$. Hang from A a weight P'' less than the sum of P and P'. The parallelogram will take up a position of equilibrium such that the cords attached to B and C will be found to form prolongations of the sides $A\ B$ and

A C, and the diagonal *A D* will be vertical. The number of inches in the diagonal will be found to be equal to the number of ounces in the weight hung from *A*. The two forces *P* and *P′* which are acting on the point *A* are represented by the lines *A B* and *A C*, and their resultant by the diagonal *A D*. This vertical resultant is balanced by the equal force *P″* acting in the opposite direction.

Fig. 11.



46. *Composition of Several Oblique Forces acting upon a Point.* — When several forces *A B*, *A C*, *A D*, and *A E* (Figure 12) are acting upon a point *A*, their resultant may be found by the following method : –

Fig. 12.

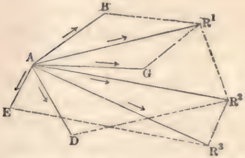
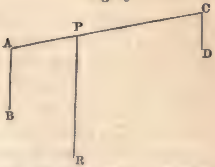


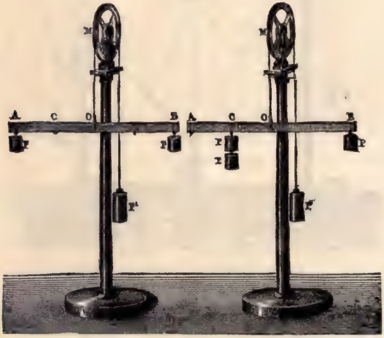
Fig. 13.



First find the resultant $A R^1$ of the two forces *A B* and *A C*; then the resultant $A R^2$ of the first resultant $A R^1$ and of the third force *A D*; and, finally, the resultant $A R^3$ of the second resultant $A R^2$ and of the fourth force *A E*. This last resultant will be the resultant of all the forces.

47. *Composition of two Parallel Forces acting in the Same Direction on Different Points.* — Suppose two parallel forces $A\,B$ and $C\,D$ (Figure 13) acting in the same direction on points at the extremities of the line $A\,C$. Their resultant $P\,R$ will have an intensity equal to the sum of the intensities of the two components, a direction the same as that of the components, and a point of application P in the line $A\,C$ at distances from A and C inversely proportional to the intensities of the forces acting on those points. That is to say, $P\,A : P\,C = C\,D : A\,B$.

Fig. 14.

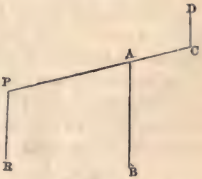


This fact may be verified by experiment as shown in Figure 14. A straight bar is suspended at its centre O by a cord which passes up over the pulley above. A weight is attached to the end of the cord just sufficient to balance the bar. If now two weights are hung from the arms of the bar, it will be found that they will be balanced by a weight equal to their sum hung upon the end of the cord, provided the distances from O to the points of suspension of the weights on the arms are in the inverse ratio of the weights. In the first case shown in the figure, the weights suspended at A and B are equal, and also the distances $O\,A$ and $O\,B$. In the second case, the weight at C is double that at B, and the distance $O\,C$ is one half that of $O\,B$. The force which balances the two forces on the arms must have the same inten-

sity and point of application as the resultant of these forces, but the opposite direction.

48. *Composition of two Parallel Forces acting in Opposite Directions on Different Points.* — Suppose two parallel forces AB and CD (Figure 15) to act in opposite directions on the points A and C. Their resultant PR will have an intensity equal to the difference of intensities of the two components, the direction of the larger component, and a point of application P in the same line as A and C, and at distances from A and C inversely proportioned to the intensities of the forces applied at those points. That is to say, $PA : PC = CD : AB$.

Fig. 15.



The more nearly equal the two forces AB and CD, the less the intensity of their resultant and the more distant its point of application. When these two forces are equal they have no resultant. This peculiar system of parallel forces is called a *couple*. There is no force that will balance it. It does not tend to produce any motion of *translation*, but one of *rotation*.

49. *Composition of Several Parallel Forces acting upon Different Points.* — To find the resultant of several parallel forces AF, BF', CF'', DF''' (Figure 16) acting upon the points A, B, C, D, first find the resultant Ir of AF and BF', then the resultant Kr' of Ir and CF'', and, finally, the resultant LR of Kr' and DF'''. This last resultant will be the resultant of all the forces.

Fig. 16.

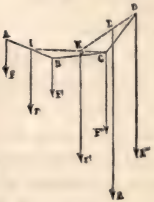
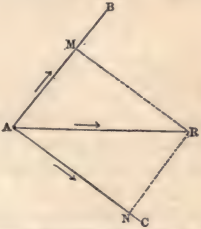


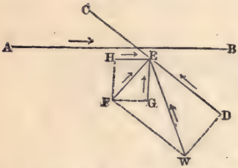
Fig. 17.



50. *Resolution of a Force into two Oblique Forces with the Same Point of Application.* — To resolve the force $A\ R$ (Figure 17) into two oblique forces having the directions of $A\ B$ and $A\ C$, draw $R\ M$ parallel to $A\ C$ and $R\ N$ parallel to $A\ B$. $A\ N$ and $A\ M$ will represent the forces required.

51. *Resolution of the Force of the Wind in the Case of a Sailing Vessel.* — Let the line $A\ B$ (Figure 18) represent the direction of the keel of the vessel; the line $C\ D$, the direction of the face of the sail; and the line $W\ E$, the direction and intensity of the wind. To find the intensity of the force which would be effective in driving the vessel forward, first decompose the force of the wind $W\ E$ into two components, one $D\ E$ tangent to the sail, and the other $F\ E$ perpendicular to the sail. This later component will be the only part of the force of the wind that will have any effect upon the sail. This force must again be decomposed into two components, one $G\ E$ perpendicular to the length of the vessel, and the other $H\ E$ in the direction of the vessel. This last component will be the only portion of the force of the wind that will be effective in moving the vessel forward.

Fig. 18.



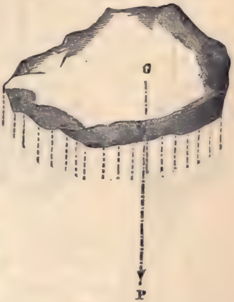
D. Gravity and Equilibrium.

52. *Law of Gravity.* — The law of gravity was discovered by Newton. It is as follows: *Every portion of matter attracts every other portion of matter with a force directly proportional to the product of the masses acted upon, and inversely proportional to the square of the distances between them.*

53. *Centre of Gravity.* — The direction of gravity at the surface of the earth is that of a plumb line. Gravity acts upon each particle of which a body is composed, and the forces of gravity acting upon the various particles of a body are parallel forces. The point of application of the resultant of these various parallel forces is called the *centre of gravity* of the body. Thus, G is the centre of gravity of the stone in Fig-

ure 19. The whole of the force of gravity acting upon a body may be considered as applied at the centre of gravity. If a force equal to the resultant of the forces of gravity be applied to the centre of gravity in the opposite direction, the body will balance or be in equilibrium.

Fig. 19.

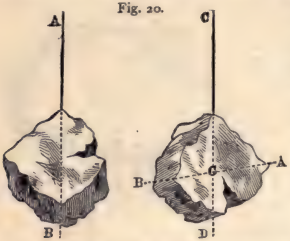


The centre of gravity may be defined as the point upon which the body will balance in every position. When a body is homogeneous throughout, the centre of gravity is at the centre of figure of the body. When the body is not homogeneous throughout, the centre of gravity is away from the centre of figure towards the denser side of the body. The centre of gravity often lies entirely outside of the material of the body, as in the case of a ring or a hollow sphere. When this is the case, the centre of gravity must be rigidly connected to the body in order to have the body balance on it. A system of bodies may have a common centre of gravity lying outside of all the bodies. The centre of gravity of two spheres will lie somewhere on a line between the centres of gravity of the spheres themselves. If the spheres have the same mass, this point will lie just midway between their centres of gravity. If one sphere has a greater mass than the other, the centre of gravity of the system will lie nearer the centre of gravity of the larger sphere. If there is sufficient difference between the masses of the spheres, their common centre of gravity may lie within the larger sphere.

54. *Experimental Method of finding the Centre of Gravity.*—Since the resultant of the forces of gravity acting upon a body and the force which balances it must act

along the same line in opposite directions, if a body be suspended so as to turn freely, its centre of gravity must be in a vertical line under the point of suspension. Hence, if we suspend any body from two points and mark the vertical lines from each point of suspension, the centre of gravity must be where these verticals cross (Figure 20).

Fig. 20.



55. *Kinds of Equilibrium.* — When a body, on being tipped a little, tends to return to its old position, it is said to be in *stable* equilibrium; when it tends to fall to a new position, in *unstable* equilibrium; and when it rests equally well in every position, in *indifferent* equilibrium.

When a body is in stable equilibrium, its centre of gravity *rises* on tipping the body; when it is in unstable equilibrium, its centre of gravity *falls* on tipping the body; and when it is in indifferent equilibrium, its centre of gravity *neither rises nor falls* on tipping the body.

56. *Equilibrium of a Body resting on a Fixed Point or Axis.* — A body resting on a point or axis can be in equi-

Fig. 21.

Fig. 22.

librium only when the centre of gravity and the point or axis of support lie in the same vertical line. This can be the case only when the centre of gravity is either directly above or below the point or axis of support. In the former case the body is in *unstable* equilibrium. This case is shown in Figure 21. *O* is the axis of support, and *G* the centre of gravity. It will be seen that gravity will tend to topple the body over as soon as it is tipped. In the latter case the body is in *stable* equilibrium. This case is shown in Figure 22. As soon as the body is tipped gravity tends to right it.

Fig. 23.

The toy called the *balancer* (Figure 23) is an illustration of stable equilibrium of a body resting on a point. The balls at the ends of the wires at each side of the figure bring the centre of gravity of the whole below the toe on which the figure is resting.

Fig. 24.

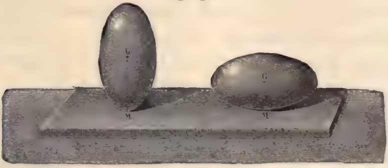
In a similar way a cork may be balanced on the point of a needle by sticking two forks into it, as shown in Figure 24.

When the centre of gravity is at the point or axis of support, the body is in *indifferent* equilibrium.

57. *Equilibrium of a Body resting on a Horizontal Plane at One Point only.* — Such a body can be in equilibrium only when its centre of gravity and the point where it touches the plane are both in the same vertical. Figure 25 represents two positions of equilibrium of an oval body on a horizontal plane. In the first case the body is in unstable equilibrium, because its centre of gravity will

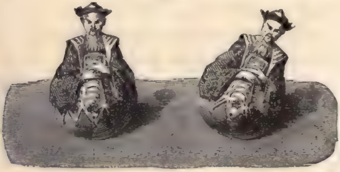
begin to fall as soon as it is tipped. In the second case the body is in stable equilibrium, because its centre of gravity is in its lowest possible position.

Fig. 25.



The toy called the *tumbler* is an illustration of stable equilibrium of a body touching a horizontal plane at one point. The centre of gravity is so low down that the body cannot be tipped without raising this point. This toy is shown in Figure 26.

Fig. 26.

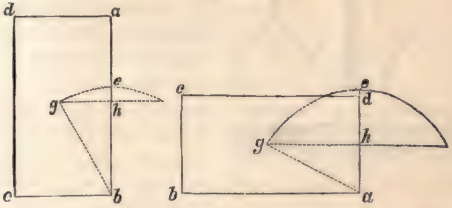


58. *Equilibrium of a Body resting on a Horizontal Plane at Several Points.* — Such a body will be in stable equilibrium when the vertical line from its centre of gravity passes within the polygon formed by joining the several points on which the body rests (Figure 27). This polygon is called the *base* of the body. The lower the centre of gravity,

Fig. 27.

and the greater the distance of its vertical from the nearest side of the base, the greater the stability of the equilibrium of the body, because the farther the body would have to be tipped, and the more its centre of gravity would have to be raised, to overturn it (Figure 28). For this reason a high load is more likely to tip over than a low one. A leaning body may be in stable equilibrium.

Fig. 28.



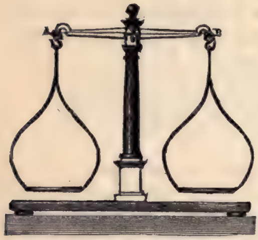
59. *Weight.* — *Weight* is the downward pressure which gravity causes a body to exert. While a body will have the same mass wherever it may be, its weight will vary with the force of gravity acting upon it. At twice the distance from the centre of the earth, a body would have only one fourth the weight it has at the surface of the earth. On the sun the same body would have 28 times the weight it has on the earth. The English unit of weight is the *pound avoirdupois;* the French unit is the *gramme.*

The weight of a body is ascertained either by finding how much it will bend a spring, as in the spring balance, or by finding how many known weights at one end of a beam will counterpoise it when placed on the other end, as in the ordinary balance. By the last method the weight of the body would be found to be the same everywhere, for it is not the weight of the body which is found in this case, but its mass. This is found by comparing the weight of a body with that of a known mass. The

weight of the mass to be weighed, and that of the mass used to counterpoise it, both change with the force of gravity.

60. *The Balance.* — The *balance* (Figure 29) consists of a rigid bar *A B*, called the *beam*, supported on an axis *O* at its centre. This axis rests upon two plates, and is just above the centre of gravity of the beam, that the beam may be in stable equilibrium. An index point attached to the beam moves over a graduated arc. When the index points to zero, the beam is in equilibrium. Two scale pans, of the same material, form, and weight, are suspended from the ends of the beam at equal distances from the axis of support. The body to be weighed is placed in one of these pans, and is counterpoised by known weights in the other.

Fig. 29.



61. *The Correctness of the Balance.* — For the balance to give true weights, it is necessary that the arms of the beam should be of exactly the same length. To test the correctness of the balance, reverse the position of the body weighed and of the weight. If the balance is true, the index will still point to zero.

As it is very difficult to make the two arms of exactly the same length, the method of *double weighing* is employed whenever great accuracy is required. By this method we may obtain exact weight, even when the arms are slightly unequal. The body to be weighed is first counterpoised with any convenient substance, as shot or sand. It is then removed, and the shot or sand is counterpoised by known weights in place of the body. These will give the exact weight of the body, since they are counterpoised by exactly the same thing under exactly the same circumstances.

62. *The Sensibility of the Balance.* — The *sensibility* of the balance depends upon the ease with which the beam is tipped.

The less the difference of weight in the two pans that will cause the beam to incline, the more sensitive the balance. The longer and lighter the beam, the nearer its centre of gravity to the axis of support, and the less the friction of this axis upon its supports, the more sensitive the balance. In carefully constructed balances, to make the friction as slight as possible, the axis is formed by the edge of a triangular piece of steel, called the *knife-edge;* and this knife-edge rests upon plates of very hard steel or of agate.

63. *Specific Gravity.*—The *specific gravity* of a substance is its weight compared with the weight of the same bulk of some standard substance. The substance commonly taken as the standard for solids and liquids is distilled water at a temperature of 39° F. A cubic foot of such water weighs 62.425 lbs. avoirdupois. The weight of a gallon of water is 10 lbs. The weight of a cubic centimetre of water is a gramme, and the weight of a litre of water is a kilogramme.

In the following table we give the specific gravities of some liquids and solids.

Liquids, at Temperature of Freezing Water.

Water, sea, ordinary	1.026	Oil, linseed	.940
Alcohol, pure	.791	" olive	.915
" proof spirit	.916	" whale	.923
Ether	.716	" turpentine	.870
Mercury	13.596	Blood, human	1.055
Naphtha	.848	Milk, of cow	1.03

Solids.

Brass, cast	7.8 to 8.4	Iron, wrought	7.6 to 7.8
" wire	8.54	Lead	11.4
Bronze	8.4	Platinum	21 to 22
Copper, cast	8.6	Silver	10.5
" sheet	8.8	Steel	7.8 to 7.9
" hammered	8.9	Tin	7.3 to 7.5
Gold	19 to 19.6	Zinc	6.8 to 7.2
Iron, cast	6.95 to 7.3	Ice	.92

Basalt	3.00	Quartz (rock crystal)	2.65
Brick	2 to 2.17	Sand	1.42
Brickwork	1.8	Fir, spruce	.48 to .7
Chalk	1.8 to 2.8	Oak, European	.69 to .99
Clay	1.92	Lignum-vitæ	.65 to 1.33
Glass, crown	2.5	Sulphur, octahedral	2.05
" flint	3.0	" prismatic	1.98

The weight of a cubic foot of any substance is equal to 62.425 lbs. avoirdupois multiplied by its specific gravity.

The weight of a cubic centimetre of any substance, in grammes, is equal to its specific gravity.

The weight of a litre (or cubic decimetre) of any substance, in kilogrammes, is equal to its specific gravity.

The weight of a gallon of any liquid, in lbs. avoirdupois, is equal to its specific gravity multiplied by 10.

QUESTIONS ON THE ABOVE TABLE.

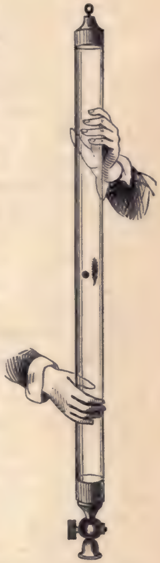
41. What is the weight of a cubic foot of mercury?
42. What is the weight of a gallon of milk?
43. How many gallons in 50 lbs. of pure alcohol?
44. What is the weight of 15 litres of ether?
45. How many litres in 8 kilogrammes of olive oil?
46. What is the weight of a cubic foot of bronze?
47. What is the weight of a cubic yard of clay?
48. What is the weight of a cubic foot of flint glass?
49. What is the weight of a cubic inch of silver?
50. How many cubic feet in a ton of ice?
51. How many cubic inches in a pound of quartz?
52. What is the weight of a cubic decimetre of silver?
53. What is the weight of a cubic metre of lead?
54. What is the weight of a cubic kilometre of basalt?
55. How many cubic centimetres in 9 kilogrammes of cast copper?

E. Falling Bodies.

64. *All Bodies fall at the Same Rate in a Vacuum.*— That light and heavy bodies fall at the same rate in a vacuum may be shown with the guinea and feather tube (Figure 30). The tube contains a bit of metal and a

feather. Exhaust the air from the tube, and invert the tube. The metal and the feather will be seen to fall through the tube at the same rate.

Fig. 30.



The reason that light and heavy bodies fall in a vacuum at the same rate is that the force of gravity acting upon a body varies directly as the mass of the body. The force of gravity on a mass of a pound is about 32 poundals; on a mass of two pounds, 64 poundals; on a mass of half a pound, 16 poundals; on a mass of one ounce, 2 poundals; etc. The force of gravity on a mass of one gramme is about 981 dynes; on a mass of a decagramme, 9810 dynes; on a mass of a decigramme, 98.1 dynes; etc. Since the intensity of the gravity acting upon a body increases just as rapidly as the mass of the body, gravity, if left to itself, would cause all bodies to fall at the same rate; for if the mass of one body is twice or thrice as great as that of another, gravity will act upon it with twice or thrice the intensity.

65. *Bodies fall with Unequal Velocities in the Air.* — A bullet will fall through the air much faster than a feather. The air offers resistance to every body falling through it. The denser a body and the less its surface, the less its motion is retarded by the air. Gold-leaf falls slowly in the air, while the same gold in the form of a solid sphere would fall almost as rapidly in the air as in a vacuum.

The resistance of the air increases with the velocity, and after a while it becomes equal to the attraction of gravity

upon a body. When this is the case, the body will gain no more velocity, but keep falling at a uniform rate. Were a body shot downward with a velocity greater than this, it would be retarded by the resistance of the air, which would then be greater than the pull of gravity, until its velocity were reduced to that at which the resistance of the air would be just equal to the pull of gravity.

66. *Acceleration produced by Gravity.* — When bodies are falling near the earth, gravity increases their velocity at the uniform rate of about 32.2 feet a second, in a vacuum. This acceleration per second produced by gravity is usually represented by g, and is called the *intensity* of gravity. It is equal to about 981 centimetres, or 9.81 metres. When a body is rising, gravity retards its velocity at the rate of 32.2 feet, or 9.81 metres a second. Were a body thrown up in a vacuum, it would be just as many seconds in falling as it is in rising, and it would reach the point it started from with the velocity it had on starting. It gains just as much velocity in falling as it lost in rising.

67. *Velocity acquired by a Body falling from a State of Rest.* — The velocity acquired by a body falling from a state of rest will be equal to the product of the intensity of gravity by the number of seconds the body has been falling. If we represent the velocity acquired by v, and the number of seconds the body has been falling by t, the formula for the velocity of a body falling from a state of rest will be $v = g\,t$.

If a body were falling from a state of rest, the number of feet of velocity it would acquire in 20 seconds would be $32.2 \times 20 = 644$; and the number of metres of velocity it would acquire would be $9.81 \times 20 = 196.2$.

68. *Distance passed over by a Body falling from a State of Rest.* — The distance passed over by a moving body is always equal to the product of its mean velocity by the time. Since falling bodies gain velocity at a uniform rate, the mean velocity of a body falling from a state of rest will be one half the velocity it has acquired. We saw, in the last section, that the

velocity acquired at any time was $g t$. Hence the mean velocity will be $\frac{1}{2} g t$. If we represent the distance passed over by s, we shall have

$$s = \tfrac{1}{2} g t \times t = \tfrac{1}{2} g t^2.$$

The distance passed over by a body falling 4 seconds from a state of rest would be equal to $16.1 \times 16 = 257.6$ feet, or to $4.9 \times 16 = 78.4$ metres.

69. *Formulæ for Falling Bodies.* —

From the formula

$$v = g t \tag{a}$$

we have

$$t = \frac{v}{g}. \tag{b}$$

Substituting this value of t in the formula

$$s = \tfrac{1}{2} g t^2, \tag{c}$$

we have

$$s = \frac{v^2}{2 g}, \tag{d}$$

$$v^2 = 2 g s,$$

$$v = \sqrt{2 g s}. \tag{e}$$

Also, by transposing the formula

$$s = \tfrac{1}{2} g t^2,$$

we have

$$t^2 = \frac{2 s}{g}$$

and

$$t = \sqrt{\frac{2 s}{g}}. \tag{f}$$

How long would it take a body falling from a state of rest to acquire a velocity of 193.2 feet?

$$t = \frac{v}{g} = \frac{193.2}{32.2} = 6 \text{ seconds.}$$

How long would it take a body falling from a state of rest to acquire a velocity of 39.24 metres a second?

$$t = \frac{v}{g} = \frac{39.24}{9.81} = 4 \text{ seconds.}$$

How far must a body fall from a state of rest to acquire a velocity of 1500 feet a second?

$$s = \frac{v^2}{2g} = \frac{2250000}{64.4} = 34938 \text{ feet.}$$

How far must a body fall from a state of rest to acquire a velocity of 800 metres a second?

$$s = \frac{v^2}{2g} = \frac{640000}{19.62} = 32619.7 \text{ metres.}$$

How long would it take a body to fall 750 feet from a state of rest, and what velocity would it acquire?

$$t = \sqrt{\frac{2s}{g}} = \sqrt{\frac{1500}{32.2}} = 6.8 \text{ seconds.}$$

$$v = \sqrt{2gs} = \sqrt{64.4 \times 750} = 219.8 \text{ feet.}$$

QUESTIONS ON FALLING BODIES.

56. How many feet of velocity would a body acquire in falling 25 seconds from a state of rest?

57. How many metres of velocity would a body acquire in falling 42 seconds from a state of rest?

58. How long would a body have to fall from a state of rest to acquire a velocity of 986 feet?

59. How long would a body have to fall from a state of rest to acquire a velocity of 25,000 centimetres a second?

60. How many feet would a body fall from a state of rest in 32 seconds?

61. How many metres would a body fall from a state of rest in 45 seconds?

62. How far would a body have to fall from a state of rest to acquire a velocity of 1200 feet a second?

63. How far would a body have to fall from a state of rest to acquire a velocity of 300 metres a second?

64. What velocity would a body acquire in falling 600 feet from a state of rest?

65. What velocity would a body acquire in falling 900 metres from a state of rest?

66. How long would it take a body to fall 700 feet from a state of rest?

67. How long would it take a body to fall 500 metres from a state of rest?

70. *Height to which a Body can rise.* — A body moving upward will continue to rise till all of its velocity is exhausted. A rising body loses velocity just as fast as a falling body gains it. Hence the height to which a body can rise with a given velocity is just equal to the height from which it must fall to gain that velocity. The height to which a body can rise will therefore be represented by the formula

$$s = \frac{v^2}{2g}.$$

In this case s is the distance a body can rise, and v the velocity with which it starts. The height to which a body can rise increases as the square of the velocity with which it starts.

68. How high could a body rise, starting with a velocity of 250 feet a second? Of 500 feet a second?

69. How high could a body rise, starting with a velocity of 150 metres a second? Of 300 metres a second?

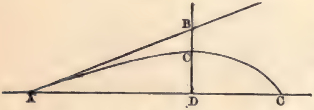
71. *Transformation of Energy in the Case of a Body Projected upward.* — When a body is projected upward, its energy on leaving the surface of the earth is entirely kinetic. As it rises, it moves slower and slower, and so loses kinetic energy, but as it is separated farther and farther from the earth, it gains potential energy. At the highest point the body reaches, its energy is entirely potential. As it falls again, it moves faster and faster, and so gains kinetic energy, but as it comes nearer and nearer the earth, it loses potential energy. While the body is rising its kinetic energy is gradually transformed into potential energy; and when it falls again, its potential energy is changed back again into kinetic energy. The energy possessed by the body is precisely the same at every point in its path. When the body strikes the earth, its energy is apparently destroyed; but when we come to

the subject of Heat, we shall see that this is not really the case.

72. *The Path of a Body Projected horizontally or obliquely.* — When a body is projected horizontally or obliquely, gravity draws it towards the earth faster and faster the longer it acts upon it, and so causes it to describe a curved path. The curve in this case would be a *parabola* were it not for the resistance of the air.

The curved line in Figure 31 shows approximately the path of a cannon-ball through the air, when fired in the direction of AB. The line AC represents the *range* of the ball, or the greatest horizontal distance it is thrown. Were it not for the resistance of the air, the range would be greatest when the cannon was pointed 45° above the horizon.

Fig. 31.



73. *Intensity of Gravity.* — The intensity of gravity varies somewhat as we pass from the equator to the poles. At the equator its intensity is sufficient to give a mass in a vacuum an acceleration of 32.088 feet per second, while at the poles it is sufficient to give a mass in a vacuum an acceleration of 32.253 feet per second. The value of g in centimetres varies from 978.10 at the equator to 983.11 at the poles. The intensity of gravity also varies with the height. At twice the distance from the centre of the earth, the intensity of gravity is only one fourth as great as at the surface of the earth.

Since a *poundal* is a force that will give to a mass of a pound an acceleration of a foot in a second, and since gravity will give a mass of a pound an acceleration of 32.2 feet a second, it follows that there are about 32.2 poundals in a pound at Greenwich, as has already been stated. A poundal is about half an ounce. The number

of poundals in a pound at any place is equal to the value of g in feet at that place.

Since gravity will give a mass of a gramme an acceleration of 981 centimetres, it follows that there are 981 dynes in a gramme of force at Greenwich. The number of dynes in a gramme at any place is equal to the value of g in centimetres at that place.

The value of g at any place is ascertained by means of a pendulum.

F. The Pendulum.

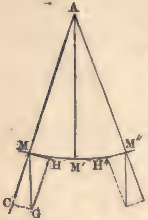
74. *The Pendulum.* — Any body free to turn on a horizontal axis which does not pass through its centre of gravity can be in stable equilibrium only when its centre of gravity is below the axis of support and in the same vertical plane with it. When pulled aside from this position of equilibrium and released, the body will vibrate back and forth across its position of stable equilibrium, until friction and the resistance of the air bring it to rest. A body suspended in this way, no matter what its shape, is called a *pendulum*. The usual form of the pendulum is that shown in Figure 32. It consists of a rod which can turn on an axis O at its upper end, and which carries a heavy lens-shaped piece of metal M, called the *ball*, at its lower end. The ball can be raised or lowered by means of the screw V.

Fig. 32.

75. *The Simple Pendulum.* — The *simple pendulum* is an ideal pendulum whose ball M' (Figure 33) consists of a single heavy particle attached to one end of a thread of invariable length and without appreciable mass, which is fastened at the other end to a fixed point A. When the thread is vertical, the pull of gravity upon the particle is in the direction of the thread, and hence it does not tend to move the particle to

the right or to the left. If the particle is drawn aside to *M*, the pull of gravity *M G* upon it will be resolved into two components: *M C* in the direction of the thread, and *M H* at right angles to this direction. The first component will be balanced by the resistance of the thread, and the second will draw the particle to the right. As *M* approaches *M′*, the component *M C* grows larger and larger, and the component *M H* smaller and smaller, vanishing entirely at *M′*. The kinetic energy which the particle has acquired in passing from *M* to *M′* will carry it up on the other side. The pull of gravity will again be resolved into two components after the particle passes *M′*, and the component *M″ H″* will now tend to stop the particle. This component will become greater and greater, and, if there were no external resistance, would finally stop the particle at *M″*, just as far to the right of *M′* as *M* was to the left of it. The particle will then return to *M′* and rise to *M* again, and so on indefinitely.

Fig. 33.



The arc *M M′* is called the *amplitude* of the vibration, and the time the particle is going from *M* to *M″* is called the *time* of vibration.

It has been found, by mathematical investigation, that *for small vibrations the time of vibration is independent of the amplitude;* also, that *the time of vibration increases as the square root of the length of the pendulum*, and *decreases as the square root of the intensity of gravity increases.* In other words, when the amplitude does not exceed 3° or 4°, the same pendulum will vibrate at the same rate, no matter what may be the amplitude of vibration; but if the pendulum is made four, nine, or sixteen times as long, it will vibrate one half, one third, or one fourth as fast; while, if a pendulum were kept of the same length, and the intensity of gravity were to become four, nine, or sixteen times as great, the pendulum would vibrate two, three, or four times as fast.

76. *The Formula of the Pendulum.* — Let T denote the time of vibration, l the length of the pendulum, g the intensity of gravity, and π the ratio of the circumference of a circle to its diameter, then the formula for the time of vibration will be

$$T = \pi \sqrt{\frac{l}{g}}. \tag{a}$$

Squaring both sides, we have

$$T^2 = \frac{\pi^2 l}{g}.$$

Clearing of fractions, we have

$$g T^2 = \pi^2 l,$$

and dividing by T^2,

$$g = \frac{\pi^2 l}{T^2}. \tag{b}$$

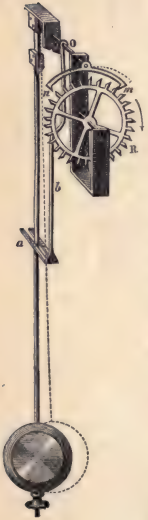
If we could construct a simple pendulum, all that we should have to do to find the intensity of gravity at a place would be to measure the length of the pendulum and count its rate of vibration. Unfortunately such a pendulum has only an ideal existence, though we may approximate sufficiently near to it for ordinary illustration by hanging a bullet of lead on a fine silk thread.

77. *The Compound Pendulum.* — Every pendulum actually used is a *compound* pendulum, consisting of a heavy weight hung from a fixed point by means of a rod of wood or metal. Each particle of such a pendulum may be regarded as a simple pendulum; but as these particles are at different distances from the point of suspension, they tend to vibrate at different rates. The particles near the point of suspension are retarded by the tendency of the particles below them to vibrate at a slower rate, while the particles near the lower end of the pendulum are accelerated by the tendency of the particles above them to vibrate more rapidly. At some point between these there must be a particle whose vibration is neither retarded nor accelerated. As this particle is vibrating at its normal rate, the distance of this particle from the point of suspension must be the length of a simple pendulum that would

vibrate at the rate of the compound pendulum. The point where this particle is situated is called the *centre of vibration;* and its distance from the point of suspension, the *virtual length* of the pendulum.

If a pendulum is inverted and suspended by its centre of vibration, the former point of suspension becomes its new centre of vibration. This remarkable property of a compound pendulum enables us readily to find the centre of vibration. We have only to reverse the pendulum, and find, by trial, the point at which it must be suspended to vibrate at the same rate as before. A pendulum constructed for this purpose is called a *reversible pendulum.*

Fig. 34.



78. *Use of the Pendulum for measuring Time.* — The most important use of the pendulum is for measuring time. A common *clock* is an instrument for keeping a pendulum in vibration, and recording its beats. The essential parts of the arrangement by which this is accomplished are shown in Figure 34. The *scape-wheel R* is turned by a weight or spring, and its motion is regulated by means of the *escapement m n.* This turns on the axis *o*, and is connected with the pendulum rod by means of the forked arm *a b.* When the pendulum is at rest, the hooks *n* and *m* of the escapement catch the teeth of the scape-wheel, and keep it from turning. As the pendulum vibrates, the hooks of the escapement alternately release and catch the teeth of the scape-wheel, and so compel it to turn slowly, and at a uniform rate. The hooks of the escapement are of such shape that each tooth of the scape-

wheel, as it slips off the hook, gives the escapement a little push so as to keep up the vibration of the pendulum.

Each tooth of the scape-wheel is caught twice during the revolution of the wheel, once by each hook of the escapement. Hence, if the scape-wheel has thirty teeth, it will make one revolution for every sixty beats of the pendulum. The axis of the scape-wheel carries the second-hand of the clock, which registers the beats of the pendulum up to sixty. The scape-wheel is connected with another which turns $\frac{1}{60}$ as fast. The axis of this wheel carries the minute-hand, which registers the revolution of the second-hand up to sixty. This second wheel is connected with a third which turns $\frac{1}{12}$ as fast as itself. The axis of this last wheel carries the hour-hand, which registers the revolution of the minute-hand up to twelve, or half a day.

79. *Transformations of Energy in the Vibrations of the Pendulum.* — When the pendulum reaches its farthest point to the right or left, its energy is entirely potential; and when its ball is at its lowest point, its energy is entirely kinetic. As the ball rises, its kinetic energy is transformed into potential energy, and as it falls again, its potential energy is transformed into kinetic energy.

The energy consumed in overcoming the friction of the axis of the pendulum and of the wheels of the clock and the resistance of the air is supplied by the falling weight or uncoiling spring; and when the store of energy in the weight or spring is consumed, it must be renewed by again raising the weight or coiling the spring in winding up the clock. This new supply of energy is drawn from the hand and arm of the person who winds the clock.

G. Machines.

80. *Simple Machines.* — A *machine* is an instrument by which a force is applied to do work. Every machine, however complicated, is made up of a very few elements, called

simple machines, or *mechanical powers*. These are the *lever*, the *wheel and axle*, the *pulley*, the *inclined plane*, the *wedge*, and the *screw*.

The force applied to work the machine is called the *power;* and the resistance overcome by the machine, the *work*. A perfect machine would be one which offered no friction or other resistance of its own. Such a machine has only an ideal existence. In every machine in actual use the work done is partly *useful* in overcoming the resistance we desire to overcome, and partly *useless* in overcoming the resistance of the machine itself. In the theory of machines the resistance of the machine itself is left out of view. The magnitude of the resistance to be overcome is represented by a rising weight, and the magnitude of the power is usually represented by a falling weight. The resistance to be overcome is technically called the *weight*.

81. *The General Law of Machines.* — The work done *by* the power *upon* a machine, and the work done *by* a machine *upon* the resistance, are simply different aspects of the same work, and hence they are equal in amount. Now the work done by a falling weight is equal to the product of the weight by the distance it falls, and the work done in raising a weight is the product of the weight by the distance it is raised. If, then, we represent the work done by the power upon the machine by a falling weight, and the work done by the machine upon the resistance by a rising weight, we arrive at the following general principle of machines: *The power multiplied by the distance through which it moves is always equal to the weight multiplied by the distance through which it moves.* This is simply saying that the work done *by* the power is equal to the work done *upon* the weight.

The following facts result from the general principle of machines, stated above: —

(1.) The faster the power moves, compared with the weight, the greater the weight it will balance.

(2.) When the power moves faster than the weight, it will balance a weight greater than itself; and when it moves slower than the weight, it will balance a weight less than itself; and when it moves just as fast as the weight, it will balance a weight equal to itself.

(3.) The power will balance a weight just as many times itself as it moves times as fast as the weight.

(4.) *In any machine, the power and weight will be in equilibrium when they are in the inverse ratio of their velocities;* that is, whichever is the smaller will move the faster, and just as many times as fast as it is times as small. The statement in italics is known as the *general law of machines*.

82. *Gain and Loss of Power in a Machine.* — When, in any machine, the power balances a weight greater than itself, there is said to be a *gain of power*, or *mechanical advantage;* and when the power balances a weight less than itself, a *loss of power*, or *mechanical disadvantage.*

When there is a gain of power there is always a corresponding loss of speed, and when there is a loss of power there is a corresponding gain of speed.

A machine might be described as an instrument by which we change the *point* at which the power acts, the *direction* in which it acts, or the *rate* at which it acts. The last change is the most important one effected by a machine. When the machine causes the power to act upon the resistance at a slower rate than it would were it applied directly to it, there is a gain of power; and when it causes it to act upon it at a quicker rate, there is a loss of power. When the machine does not change the rate, there is neither gain nor loss of power. The general law given above is applied to every machine. When we take up the different simple machines, we shall give the special law of each; and that is the law which concerns the relative velocities of the power and weight.

QUESTIONS ON THE GENERAL LAW OF MACHINES.

70. In a machine, the power moves 25 inches while the weight is moving 35 inches. What weight would be balanced by 63 pounds of power?

If we denote the power by P, the weight by W, the velocity of the power by VP, the velocity of the weight by VW, and the distances passed over by the power and weight, respectively, by DP and DW, then we shall have, in the above example,

$$VP = \tfrac{5}{7}\ VW$$
$$P = \tfrac{7}{5}\ W$$
$$63 = \tfrac{7}{5}\ W$$
$$63 \div \tfrac{7}{5} = 45$$
$$W = 45 \text{ pounds.}$$

71. In a machine, a power of 27 pounds balances a weight of 45 pounds. How far does the power move while the weight moves 60 inches?

$$P = \tfrac{3}{5}\ W$$
$$\therefore\ VP = \tfrac{5}{3}\ VW$$
$$DP = \tfrac{5}{3} \times 60 = 100 \text{ inches.}$$

72. In a machine, the power moves 56 inches while the weight moves 21 inches? What power will balance a weight of 600 pounds?

73. In a machine, the power moves 35 inches while the weight is moving 63 inches. What weight will be balanced by 250 pounds of power?

74. In a machine, the power moves 15 centimetres while the weight moves 40 centimetres. What power will balance a weight of 90 grammes?

75. In a machine, the power moves 24 centimetres while the weight is moving 56 centimetres. What weight would be balanced by 130 grammes of power?

76. In a machine, a power of 28 pounds balances a weight of 49 pounds. How far will the power move while the weight moves 20 inches?

77. In a machine, a power of 40 pounds balances a weight of 32 pounds? How far will the weight move while the power is moving 30 inches?

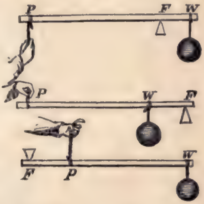
78. In a machine, a power of 50 grammes balances a weight

of 80 grammes. How far will the power move while the weight is moving 15 centimetres?

79. In a machine, a power of 81 grammes balances a weight of 63 grammes. How far will the weight move while the power is moving 25 centimetres?

83. *The Lever.* — The *lever* is a rigid bar, capable of turning upon a fixed point or axis. The point on which the lever turns is called the *fulcrum*.

Fig. 35.

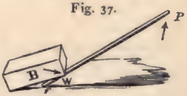


Different forms of the lever are shown in Figure 35. *F* is the fulcrum, *W* the weight, and *P* the power.

When the *fulcrum* is between the power and weight, the lever is said to be of the *first order;* when the *weight* is between the fulcrum and power, the lever is said to be of the *second order;* and when the *power* is between the fulcrum and weight, the lever is said to be of the *third order.*

Fig. 36.

Fig. 37.



A bar used for raising a weight is a lever. When it is used as shown in Figure 36, it is a lever of the first order. When it is used as shown in Figure 37, it is a lever of the second order. A fishing-rod (Figure 38) is a lever of the third order.

Fig. 38.

The *arms* of a lever are the distances from the fulcrum to the points where the power and weight are applied, in case the lever is straight; or the distance from the fulcrum to the lines which show the direction of the power and weight, in case the lever is bent.

In Figure 35, *FP* is in each case the *power arm*, and *F W* the *weight arm*. In Figure 39, the dotted lines, which are supposed to be drawn from the fulcrum perpendicularly to the directions in which the weight and power act, are the arms of the bent lever, *a b f c*.

Fig. 39.

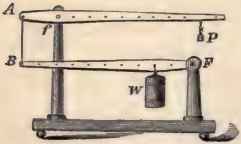
84. *The Special Law of the Lever.* — The special law of the lever is, that *the velocities of the power and weight are in the direct ratio of the lengths of the arms to which they are applied;* that is, if one arm of the lever be three times as long or one-third as long as the other, the power or weight applied to this arm will move three times as fast or one third as fast as the one applied to the other arm.

There will be a gain of power in the lever whenever the power arm is the longer ; for the power will then move the faster, and will balance a weight greater than itself. There will be a loss of power when the power arm is the shorter ; for the power will then move the slower, and will balance a weight less than itself.

In a lever of the second order there will always be a gain of power, and in a lever of the third order a loss of power. In the lever of the first order there will be a gain or loss of power, or neither, according as the fulcrum is nearer the weight, or nearer the power, or midway between the two.

85. *The Compound Lever.* — Sometimes two or more simple levers are combined, as shown in Figure 40. Suppose that *P* be five times as far from the fulcrum *f* as *A* is, the point *P* will then move five times as fast as the point *A*, and a pull of one pound on *P* will exert a pull of five pounds on *A*. If *B* is five times as far from the fulcrum *F* as *W* is, the five pounds of

Fig. 40.



pull on B will exert twenty-five pounds of pull at W. In this case one pound of pull exerted at P will balance twenty-five pounds at W; but it would be found on trial that by pulling P down one inch, W would be raised only one twenty-fifth of an inch.

Such a combination of levers is called a *compound lever*.

QUESTIONS ON THE LEVER.

80. In a lever, the power arm is 18 inches and the weight arm is 42 inches. What weight would be balanced by 60 pounds of power?

Denote the power arm by PA, and the weight arm by WA.

$$PA = \tfrac{3}{7}\, WA$$
$$\therefore VP = \tfrac{3}{7}\, VW$$
$$\therefore P = \tfrac{7}{3}\, W$$
$$60 = \tfrac{7}{3}\, W$$
$$60 \div \tfrac{7}{3} = 25\tfrac{5}{7}$$
$$W = 25\tfrac{5}{7} \text{ pounds.}$$

81. In a lever, the power arm is 36 inches, and the weight arm 27 inches. What power will balance a weight of 75 pounds?

82. In a lever, the power arm is 14 decimetres long, and the weight arm 21 decimetres. What weight would be balanced by 70 grammes of power?

83. In a lever, the power arm is 49 decimetres long, and the weight arm 28 decimetres. What power would balance a weight of 17 kilogrammes?

84. In a lever, a power of 30 pounds balances a weight of 50 pounds, and the power arm is 80 inches long. What is the length of the weight arm?

85. In a lever, a power of 70 pounds balances a weight of 20 pounds, and the weight arm is 30 inches long. What is the length of the power arm?

86. In a lever, a power of 150 grammes balances a weight of 250 grammes, and the power arm is 18 decimetres in length. What is the length of the weight arm?

87. In a lever, a power of 270 grammes balances a weight of 120 grammes, and the weight arm is 48 decimetres in length. What is the length of the power arm?

88. In a lever of the first order, a power of 30 pounds balances a weight of 40 pounds, and the power arm is 27 inches long. What is the length of the lever?

89. In a lever of the first order, a power of 55 grammes balances a weight of 35 grammes, and the weight arm is 13 decimetres long. What is the length of the lever?

90. In a lever of the second order, a power of 16 pounds balances a weight of 56 pounds, and the length of the weight arm is 34 inches. What is the length of the lever?

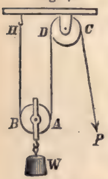
91. In a lever of the second order, the length of the lever is 65 decimetres, and a power of 24 grammes will balance a weight of 64 grammes. What is the length of the weight arm?

92. In a lever of the third order, the length of the lever is 80 inches, and the length of the power arm 30 inches. What weight would be balanced by 47 pounds of power?

93. In a lever of the third order, the length of the lever is 28 decimetres, and the length of the power arm is 12 decimetres. What power will balance 18 grammes of weight?

86. *The Pulley.* — The *pulley* is a small grooved wheel arranged so as to turn freely in a frame called the *block*. The pulley is an instrument in which power is applied to do work by means of a cord instead of a bar, as in the case of the lever. The wheel of the pulley serves simply to diminish friction at the points over which the cord is drawn.

Fig. 41.



In Figure 41, the block of the pulley $D\ C$ is fastened to the beam above, so as to be stationary, while the block of the pulley $A\ B$ is free to move up and down. The former is called a *fixed* pulley; and the latter, a *movable* pulley. A fixed pulley serves simply to change the direction in which the power acts.

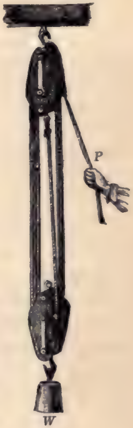
87. *Systems of Pulleys with one Cord.* — In Figures 42, 43, and 44, are shown systems of pulleys with a single cord, that is, in which one cord passes over all the

pulleys. The power is applied to the end of the rope, and the weight is attached to the movable block. In

Fig. 42.

Fig. 43.

Fig. 44.



the first case, on raising the movable block one inch, three inches of rope will be released, since the rope comes three times to that block. In this case the power will move three times as fast as the weight. In the second case, on raising the movable block one inch, four inches of rope will be released, since the rope comes four times to this block. In this case the power will move four times as fast as the weight. In the third case the power will move six times as fast as the weight.

The special law of a system of pulleys with a single rope is that *the velocities of the power and weight are in the inverse ratio of the number of times the rope comes to each.* As the cord always comes once to the power, the power will balance a weight as many times itself as the rope comes times to the block bearing the weight.

QUESTIONS ON PULLEYS WITH SINGLE ROPE.

94. In a system of pulleys with a single rope, the rope comes 13 times to the block bearing the weight. What weight would be balanced by 75 pounds of power?

95. In a system of pulleys with a single cord, the cord comes 9 times to the block bearing the weight. What power would balance 19 grammes of weight?

96. In a system of pulleys with a single rope, a power of 13 pounds balances a weight of 91 pounds. How many times does the rope come to the block bearing the weight?

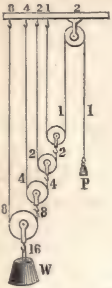
97. In a system of pulleys with a single rope, a power of 72 grammes balances a weight of 792 grammes. How many times does the rope come to the block bearing the weight?

88. *Systems of Pulleys with more than one Rope.* — The law of the pulley is sometimes stated as follows: *A stretched rope must have the same tension throughout its whole length.*

Figure 45 represents a system of pulleys in which two ropes are used. Here a weight of four pounds is balanced by a power of one pound. The parts of the rope $A D$ and $A B$ must each have a tension equal to the power. The rope $A C B$ balances the two tensions, $B P$ and $B A$, and must therefore have a tension of twice the power. The three tensions supporting the pulley A amount therefore to four times the power.

Fig. 45.

Fig. 46.

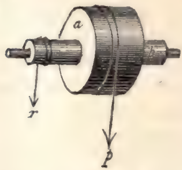


In the system shown in Figure 46 four ropes are used. The tensions of the several ropes will be readily understood from the numbers. It will be seen that in this case the power is doubled by each movable pulley which is added; but, as in all the systems we have examined, what is gained in power is lost in speed.

89. *Wheel and Axle.* — The *wheel and axle* consists of a wheel, or drum, A (Figure 47), mounted on an axle B. The power and weight are applied to ropes which pass,

one over the wheel and the other over the axle, in opposite directions, so that one unwinds as the other winds up.

Fig. 47.

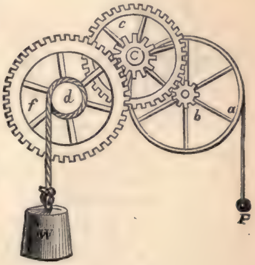


The power and weight are really applied to the wheel and axle at the point where the rope touches each, that is, at the end of the radius of each. The one applied to the wheel moves the faster, and just as many times faster as the circumference or the radius of the wheel is times the circumference or the radius of the axle.

The special law of the wheel and axle is that *the velocities of the power and weight are in the direct ratio of the radii to which they are applied.* When the power is applied to the wheel, there is a gain of power; and when it is applied to the axle, there is a loss of power.

The chief use of the wheel and axle in machinery is in transmitting motion of rotation from one piece to another, with or without a change of velocity. For an increase of velocity, a large wheel must act upon a small one; and for a diminution of velocity, a small wheel must act upon a large one. When there is to be no change of velocity, the wheels must both be of the same size.

Fig. 48.



90. *Cog-Wheels.* — There are various ways in which the axle of one wheel is made to act on the circumference of another. Sometimes the one turns the other by rubbing against it, or by *friction.* The most common way, however, is by means of *teeth* or *cogs* raised on the surfaces of the wheels and axles. The cogs on the

wheel are usually called *teeth*, while those on the axle are called *leaves*, and the part of the axle from which they project is called the *pinion*.

91. *The Gain of Power by Wheel-Work.* — In the train of wheels in Figure 48, if the circumference of the wheel a is 36 inches, and that of the pinion b is 9 inches, or one fourth as great, a power of one pound at P will exert a force of four pounds on b. If the circumference of the wheel e is 30 inches, and that of the pinion C 10 inches, the four pounds acting on the former will exert a force of twelve pounds on the latter. If the circumference of the wheel f is 40 inches, and that of the axle d 8 inches, the twelve pounds acting on f will exert a force of sixty pounds on d. One pound at P will then balance sixty pounds at W.

But in this case, as in all others, what is gained in power is lost in speed; since the one pound at P must move through sixty inches in order to raise the sixty pounds at W one inch.

Cog-wheels which have their teeth arranged as in Figure 48 are called *spur-wheels*. If the teeth project from the

Fig. 49.

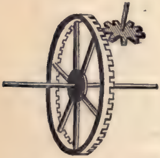
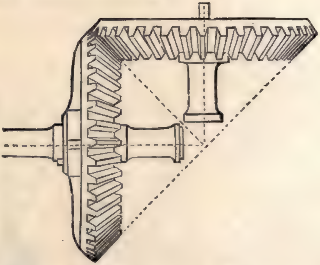


Fig. 50.



side of the wheel, as in Figure 49, it is called a *crown-wheel*. If their edges are sloped, as in Figure 50, the wheel is called a *bevel-wheel*. Bevel-wheels may be inclined to each other at any angle.

In all cases the lines which mark the slope of the teeth of the two wheels will meet at the same point, as in Figure 50.

92. *Belted Wheels.* — Another way in which wheels and axles may be made to act upon one another is by means of a *belt*, or band, passing over them both. They may thus be at any distance apart, and may turn either the same way or contrary ways, according as the belt does or

Fig. 51.

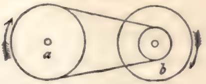
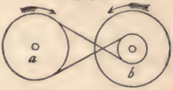


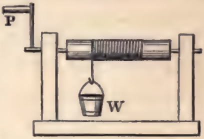
Fig. 52.



does not *cross* between them (Figures 51 and 52). A cog-wheel and its pinion must, of course, always turn in contrary directions.

93. *The Windlass and Capstan.* — The *windlass* is a horizontal barrel turned by means of a crank or spokes (Figure 53). It may be regarded as a modification of the wheel and axle, the crank taking the place of the wheel. The *capstan* is an upright drum turned by means of levers, which may be removed at pleasure.

Fig. 53.



QUESTIONS ON THE WHEEL AND AXLE.

98. The radius of a wheel is 40 inches, and that of its axle 15 inches. What weight on the axle would be balanced by 50 pounds of power on the wheel?

Denote the radius of the wheel by RW, and that of the axle by RA.

$$RW = \tfrac{8}{3}\,RA$$
$$\therefore\ VP = \tfrac{8}{3}\,VW$$
$$\therefore\ P = \tfrac{3}{8}\,W$$
$$50 = \tfrac{3}{8}\,W$$
$$50 \div \tfrac{3}{8} = 133\tfrac{1}{3}$$
$$W = 133\tfrac{1}{3} \text{ pounds.}$$

99. The radius of a wheel is 18 decimetres, and that of its axle 12 decimetres. What weight on the wheel would be balanced by 32 grammes of power on the axle?

100. In a wheel and axle, a power of 63 pounds on the axle balances a weight of 35 pounds on the wheel. The radius of the wheel is 16 decimetres. What is the radius of the axle?

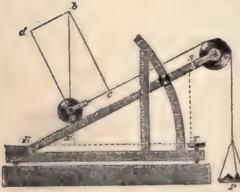
101. A power of 21 pounds on the wheel balances a weight of 77 pounds on the axle. The radius of the axle is 5 inches. What is the radius of the wheel?

94. *The Inclined Plane.* — An *inclined plane* is simply an inclined surface. It is easier to roll a body up an inclined surface than to raise the body vertically to the same height. The longer the plane, the easier it is to roll the body up it. The reason is obvious. The body must be raised against the action of gravity; and by rolling the body up the inclined surface, the power is compelled to act the length of the surface to raise the weight the height of it.

The special law of the inclined plane is that *the velocities of the power and weight are in the ratio of the length of the plane to its height.* Since the power and weight are in the inverse ratio of their velocities, it follows that *the power will be to the weight as the height of the plane is to its length.*

The law of the inclined plane may be demonstrated by means of the apparatus represented in Figure 54. R S represents the section of a smooth piece of hard wood hinged at R; by means of a screw it can be clamped at any angle x against the arc-shaped support; a is a metal cylinder, to the axis of which is attached a string passing over a pulley to a scale-pan P.

Fig. 54.



It is thus easy to ascertain by direct experiments what weight must be placed in the pan P in order to balance a roller of any given weight.

The line $R\ S$ represents the *length*, $S\ T$ the *height*, and $R\ T$ the *base* of the inclined plane.

In ascertaining the conditions of equilibrium we have a useful application of the parallelogram of forces. Let the line $a\ b$ (Figure 54) represent the force which the weight W of the cylinder exerts acting vertically downward; this may be decomposed into two others, — one, $a\ d$, acting at right angles against the plane, and representing the *pressure* which the weight exerts against the plane, and which is counterbalanced by the reaction of the plane; the other, $a\ c$, representing the component which tends to move the weight down the plane, and which has to be held in equilibrium by the weight, P, equal to it and acting in the opposite direction.

It can be readily shown that the triangle $a\ b\ c$ is similar to the triangle $S\ R\ T$, and that the sides $a\ c$ and $a\ b$ are in the same proportion as the sides $S\ T$ and $S\ R$. But the line $a\ c$ represents the power, and the line $a\ b$ the weight; hence

$$S\ T : S\ R = P : W.$$

95. *The Wedge.* — Instead of lifting a weight by moving it along an inclined plane, we may do the same thing by pushing the inclined plane under the weight. When used in this way the inclined plane is called the *wedge*. A wedge which is used for splitting wood has usually the form of a double inclined plane, as in Figure 55. The law of the wedge is the same as that of the inclined plane, but since a wedge is usually driven by a blow instead of a force acting continuously, it is difficult to illustrate this law by experiments.

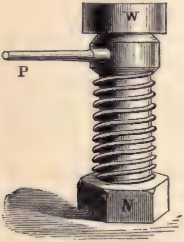
Fig. 55.

96. *Uses of the Wedge.* — The wedge is especially useful when a large weight is to be raised through a very short distance. Thus, a tall chimney, the foundation of which has settled on one side, has been

made upright again by driving wedges under that side. So, too, ships are often raised in docks by driving wedges under their keels. Cutting and piercing instruments, such as razors, knives, chisels, awls, pins, needles, and the like, are different forms of wedges.

97. *The Screw.* — In Figure 56, we have a machine called the *screw*. It is a movable inclined plane, in which the inclined surface winds round a cylinder. The cylinder is the *body* of the screw, and the inclined surface is its *thread*.

Fig. 56.



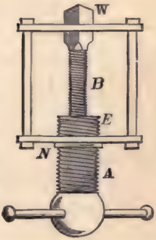
The screw usually turns in a block *N*, called the *nut*. Within the nut there are threads exactly corresponding to those on the screw. The threads of the screw move in the spaces between those of the nut.

The power is usually applied to the screw by means of a lever *P*. Sometimes the screw is fixed and the nut is movable, and sometimes the nut is fixed and the screw movable.

98. *Hunter's Screw.* — In Figure 56, if we turn the lever *P* round once, the weight *W* will be raised a distance equal to the space between two threads of the screw. Were the lever of such a length that its end would describe a path 10 feet long, and were the distance between two threads of the screw $\frac{1}{4}$ of an inch, and were there no friction in the nut, a power of one pound applied to the end of the lever would exert a force of 480 pounds upon the weight. It will be seen from this that the mechanical advantage of the screw may be increased by increasing the length of the lever by which it is turned, or by bringing the threads closer together. But if the threads are brought too near together, they become too weak; while, on the other hand, the machine becomes unwieldy if the lever is made too long. These objections have been obviated in the *differential* screw,

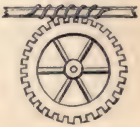
contrived by Hunter, and shown in Figure 57. *N* is the nut in which the screw *A* plays. We will suppose that the threads of this screw are $\frac{1}{10}$ of an inch apart. This screw *A* is a hollow nut, which receives the smaller screw *B*, the threads of which we will suppose to be $\frac{1}{11}$ of an inch apart. This small screw is free to move upward and downward, but is kept from turning round by means of the framework. If by means of the handle the larger screw is turned round ten times, and the smaller screw is allowed to turn round with it, the point *W* will rise an inch. If we then turn the smaller screw ten times backward, the point *W* will move down $\frac{10}{11}$ of an inch. The effect of both these motions will be to raise the point *W* $\frac{1}{11}$ of an inch. But if the smaller screw has been turned upward ten times and then downward ten times, the effect is the same as if it had been kept from turning. Hence, by turning the lever round ten times, the point *W* will be raised $\frac{1}{11}$ of an inch, or the *difference* of the distances between the threads in the two screws, while the point *E* has been raised an inch. According to the law of machines, then, the pressure at *W* is eleven times as great as at *E*.

Fig. 57.



99. *The Endless Screw.* — In Figure 58, the thread of the screw works between the teeth of the wheel. Hence, if the screw is turned, the wheel must turn. Since as fast as the teeth at the left escape from the screw those on the right come up to it, the screw is acting upon the wheel continually. Hence this machine is called the *endless screw*.

Fig. 58.



III.

PHYSICS.

I.

STATES OF MATTER.

A. Three States of Matter.

100. *The Three States.*— Matter exists in three different *states*, known as the *solid*, the *liquid*, and the *gaseous*. Ice is a solid, water is a liquid, and steam and air are gases. While the substance of a body depends upon its atomic structure, the state of a body depends upon its molecular structure. Hence the state of matter is a *physical* condition, and changes of state are *physical* changes.

101. *Cohesion in the Different States of Matter.*— The different states of matter depend upon the strength of the attraction of cohesion among the molecules. This is comparatively strong in solids, very weak in liquids, and entirely wanting in gases. The molecules of some solids are bound together much more firmly than those of others by cohesion; but even when this bond is weakest, the molecules manifest a disposition to maintain their relative positions in the body, and the body to preserve its form. In liquids, the bond of cohesion is so slight that the molecules manifest no disposition to maintain their relative positions in the body, nor does the body tend to preserve its form. Gases are not held together at all by cohesion, but only by gravity.

102. *Molecular Motion in the Different States of Matter.* — The molecules are, undoubtedly, in incessant motion in every state of matter, but their freedom of motion is very different in the different states. In solids, the molecules, when left to themselves, have fixed positions, within which they can move to a limited extent, but from which they can never escape. When left to themselves, the molecules of a solid never move around among themselves so as to change their relative positions. A molecule in the interior of a mass can never work its way to the surface, nor can one at the surface work its way into the interior.

In liquids, the molecules are all the time moving about among themselves in the interior of the mass with the utmost freedom. No molecule is confined within particular limits within the mass, but every molecule is continually moving to and fro in every direction throughout the entire mass. They, however, never escape from the influence of cohesion. So long as they are in the interior of the mass, the cohesion of the molecules on one side of them is exactly balanced by that of the molecules on the other side ; hence it does not interfere with the freedom of their motion. But as the molecules come to the surface, they experience only the pull of the molecules behind them, and this is usually sufficient to stop their outward motion and to cause them to return into the interior of the mass. In gases, the molecules are moving without the slightest restraint from cohesion ; hence they move in straight lines. They are continually striking together and rebounding again, but after each rebound they move in straight lines till they encounter other molecules. There is no force acting within the mass of a gas which tends to check the motion of the molecules at any point ; hence gases do not, like liquids, tend to assume a definite surface.

103. *The Distances between the Molecules in the Different States of Matter.* — As a rule, the molecules are nearer to-

gether in solids than in liquids, and in liquids than in gases. The molecules of steam are about seventeen hundred times as far apart as those of water.

104. *Behavior of the Different States of Matter when Small Portions of each are placed in Empty Vessels.* — If a small portion of a solid is placed in an empty vessel, it will either not conform to the shape of the vessel at all, or, in the case of a soft solid, only slowly and imperfectly. This is owing to the tendency of a solid to maintain its shape. If a small amount of a liquid is put into an empty vessel, it will conform at once and perfectly to the shape of the vessel, but it will not completely fill it. The liquid will sink to the lowest part of the vessel, and will be separated by a definite surface from the space in the upper part of the vessel. This is because the cohesion of the liquid checks the outward motion of the molecules, and so keeps them from moving away from the mass. If any portion of a gas, however small, is placed in an empty vessel, however large, the gas will completely fill the vessel. This is because there is nothing to check the outward motion of the molecules of the gas, save the walls of the vessel in which it is inclosed.

B. Fluids.

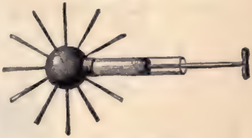
105. *Fluids.* — Owing to their freedom of molecular motion, liquids and gases have several characteristics in common. They are, accordingly, often classed together as *fluids*. This appellation is derived from the readiness with which portions of each of these states of matter *flow* over or among each other.

106. *Pascal's Law.* — One of the most remarkable characteristics of a fluid is the way in which it transmits any pressure that is brought to bear on it. *If any pressure is brought to bear on any portion of the surface of a fluid which fills a closed vessel, a pressure just equal to it will be transmitted through the fluid to every equal portion of surface.* This

law was enunciated by Pascal, and is known as *Pascal's law.*

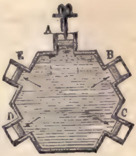
The following experiment shows that pressure is transmitted in all directions by a fluid. A tube (Figure 59) is provided with a piston and fitted with a hollow globe, which is pierced with a number of orifices, arranged in a circle around it. Fill the globe and tube with water. If the piston is forced in, the water spouts out of all the orifices, and not merely those opposite the piston.

Fig. 59.



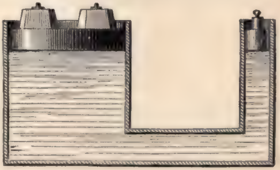
Conceive a vessel of any form, in the sides of which are a number of cylindrical apertures, all of the same size, and closed with movable pistons, as shown at *A*, *B*, *C*, *D*, and *E* (Figure 60). Suppose a pound of pressure brought to bear upon *A*. A pound of pressure will be transmitted to each of the other pistons in the direction of the arrows. If the piston *B* had only half the surface of *A*, it would receive only ½ a pound of pressure; if it had twice the surface of *A*, it would receive 2 pounds of pressure; if it had three times the surface of *A*, it would receive 3 pounds of pressure; and so on.

Fig. 60.



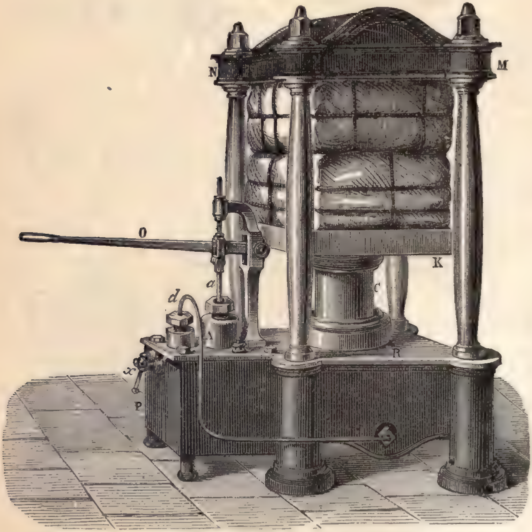
107. *The Hydraulic Press.*—It follows, from what has just been shown, that by means of a liquid a small pressure upon a small surface may be made to exert a great pressure upon a large surface. In Figure 61 we have two cylinders, with a piston in each. Suppose

Fig. 61.



that the surface of the larger piston is fifty times that of the smaller; if the latter is pressed downward by a weight of one pound, an upward pressure of one pound will be brought to bear upon each portion of the surface of the large piston equal to that of the small piston. The whole upward pressure on the large piston will then be fifty times the downward pressure on the small one. If the surface of the larger piston had been one hundred times that of the smaller, one pound on the latter would have balanced one hundred on the former; and so on.

Fig. 62.



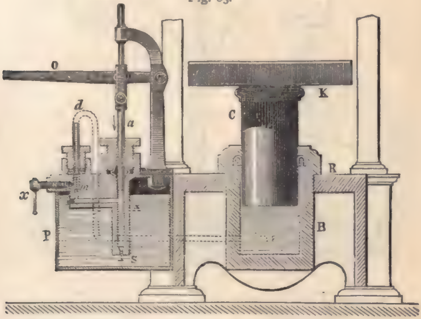
The *hydraulic press* is constructed on the principle illustrated above. One form of this press is shown in Fig-

ures 62 and 63. The two cylinders *A* and *B* are connected by the pipe *d*. The piston *a*, in the cylinder *A*, is worked by the handle *O*, and forces water into the large cylinder *B*, where it presses up the piston *C*. If the end of the piston *C* is 1000 times as large as that of the piston *a*, a pressure of 2 pounds on *a* would exert a pressure of 2000 pounds, or one ton, upon *C*. If a man, in working the handle *O*, forces down the piston *a* with a pressure of 50 pounds, he would bring to bear upon *C* a pressure of 25 tons.

This press is used for pressing cotton, hay, cloth, etc., into bales; for extracting oil from seeds; for testing cannon, boilers, etc.; and for raising ships out of the water.

The hydraulic jack is a form of the hydraulic press, adapted to raising heavy weights.

Fig. 63.

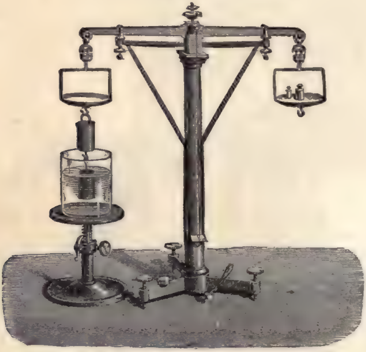


108. *Archimedes's Principle.—A body in a fluid is buoyed up by a force equal to the weight of the fluid it displaces.* This fact was discovered by Archimedes, and is therefore designated by his name.

Archimedes's principle may be verified by the following experiment. A brass cylinder is constructed so as just to fill a cup. The cup and cylinder are hung from one pan

of a balance (Figure 64) and counterpoised in the air by weights in the other pan. The cylinder is then allowed to hang in a vessel of water. The weights overbalance the cup and cylinder, showing that the water lifts the cylinder up. Equilibrium is restored by filling the cup with water. When the cup is full, the beam of the balance will be horizontal, and the cylinder will be completely in the water, showing that the cylinder is buoyed up by the water with a force equal to the weight of the cup full of water, or to the weight of the water displaced by the cylinder.

Fig. 64.

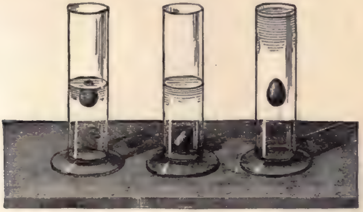


109. *Forces acting upon a Body immersed in a Fluid.* — Every body immersed in a fluid is subjected to two forces: one equal to its own weight, which tends to make the body sink; the other equal to the weight of the liquid displaced, which tends to make the body rise.

When a body displaces more than its own weight of a fluid, it will rise in that fluid; when it displaces less than its own weight, it will sink; and when it displaces just its own weight, it will remain suspended wherever it happens to be.

These three cases may be illustrated by putting an egg into salt and fresh water (Figure 65). When the egg is

Fig. 65.



placed in salt water, it rises to the surface because it displaces more than its own weight of the brine. When it is put into the fresh water, it sinks to the bottom because it displaces less than its own weight of the water. When it is put into a proper mixture of fresh water and brine, it will remain suspended in the fluid, because it displaces just its own weight of the mixture.

Fig. 66.

110. *Floating Bodies.* — Every body floating in a fluid displaces just its own weight of the fluid. This is equally true of a ship floating in water, or a balloon floating in the air (Figure 66). The more heavily the ship is loaded, the deeper she sinks into the water. By throwing out the sand which is used as ballast, the balloon is made lighter, so as to displace more than its own weight of air. It then rises till it comes into more highly rarefied

air, where it displaces just its own weight, when it again floats along at the same level. By opening the valve, so as to allow some of the gas to escape, the balloon becomes less in bulk, and so displaces less than its own weight of air. It then sinks until it again displaces its own weight.

The appendage at the side of the balloon (Figure 66) is called a *parachute*. The object of the *parachute* is to allow the aeronaut to leave the balloon, by giving him the means of lessening the rapidity of his descent. It consists of a large circular piece of cloth (Figure 67) about 16 feet in diameter, which, by the resistance of the air, spreads out like a gigantic umbrella. In the centre there is an aperture, through which the air, compressed by the rapidity of the descent, makes its escape; for otherwise oscillations might be produced, which, when communicated to the boat, would be dangerous.

Fig. 67.

In Figure 66, the parachute is attached to the network of the balloon by means of a cord, which passes round a pulley, and is fixed at the other end to the boat. When the cord is cut the parachute sinks, at first very rapidly, but more slowly as it becomes distended, as represented in the figure.

111. *Equilibrium of Floating Bodies.* — The point of application of the resultant of the upward pressure of a fluid upon the various parts of a floating body is called the *centre of buoyancy.* In Figures 68 and 69, the centre of gravity of the floating body is marked G, and the centre of buoyancy O; and the direction in which the resultants of gravity and buoyancy act upon these points is indicated by the arrows.

In order that a floating body be in equilibrium, it is necessary that it should displace its own weight of the fluid, and that the

centres of gravity and buoyancy should be on the same vertical line. Unless the latter condition is fulfilled, the forces of gravity and buoyancy would tend to turn the body over. This is evident from Figure 68. When a body is completely immersed in a fluid, it can be in stable equilibrium only when its centre of gravity is below the centre of buoyancy, for in this case only would the action of the two forces tend to right the body when tipped. This is also evident from Figure 68.

When the body is only partially immersed, it may be in stable equilibrium when the centre of buoyancy is below the centre of gravity; for when the body tips, the figure of the liquid displaced changes, and the centre of buoyancy shifts towards the side on which the body is more deeply immersed, so that the two forces may still tend to right the body, as shown in Figure

Fig. 68.

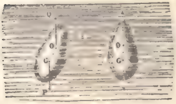
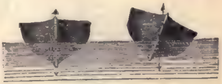


Fig. 69.



69. The two forces will tend to right the body as long as the vertical from the centre of gravity falls within the centre of buoyancy. If the vertical falls beyond the centre of buoyancy, the two forces will tend to overturn the body. The higher the centre of gravity, the more likely the vertical to fall beyond the centre of buoyancy. Hence a small boat is more likely to upset when the persons in it stand than when they sit.

112. *Method of finding the Specific Gravity of Solids and Liquids.* — To find the specific gravity of a solid or liquid, it is necessary to find the weight of a volume of water equal to that of a portion of the solid or liquid whose specific gravity is to be found. By means of Archimedes's principle, the weight of this volume of water is easily found.

Suppose we wish to find the specific gravity of copper. Fasten the piece of copper to one pan of the balance by a fine thread (Figure 70), and counterpoise it in the air with

weights in the other pan. Suppose it to weigh 125.35 grains. Then suspend it in a vessel of water and restore the equilibrium by placing weights in the pan supporting the copper. Suppose it to require 14.24 grains. This, according to Archimedes's principle, is the weight of the water displaced by the copper, or of a volume of water equal to that of the copper. The specific gravity of the copper is $\frac{125.35}{14.24} = 8.8$.

Fig. 70.

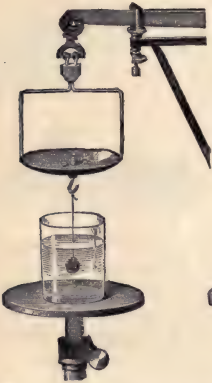
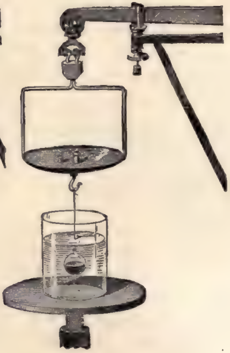


Fig. 71.



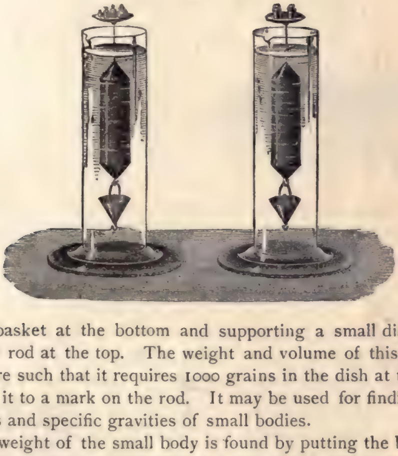
When the body whose specific gravity we wish to find is lighter than water, we must fasten it to a heavy body to sink it. We then find, by the above method, the weight of the water displaced by the sinker alone, and by the sinker and light body together. The difference between the two will be the weight of the water displaced by the lighter body.

The specific gravity of a liquid may be found by the following method. A glass ball, weighted with mercury inside, is first accurately weighed in air. It is then immersed

in a vessel of alcohol or other liquid under examination (Figure 71), and equilibrium is restored by adding weights to the pan from which the ball is suspended. Suppose 35.43 grains are required. This will be the weight of the ball's volume of alcohol. Next immerse the ball in water, and restore the equilibrium as before. Suppose it requires 44.28 grains this time. This will be the weight of the ball's volume of water. The specific gravity of alcohol will be $\frac{35.43}{44.28} = .8$.

113. *Nicholson's Hydrometer.* — This instrument (Figure 72) consists of a hollow cylinder of metal with conical ends, carry-

Fig. 72.



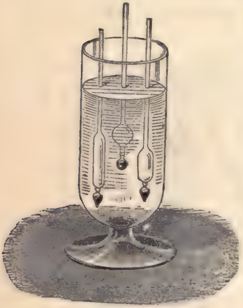
ing a basket at the bottom and supporting a small dish on a slender rod at the top. The weight and volume of this instrument are such that it requires 1000 grains in the dish at the top to sink it to a mark on the rod. It may be used for finding the weights and specific gravities of small bodies.

The weight of the small body is found by putting the body in the dish at the top, and adding weights enough to sink the instrument to the mark on the rod. The difference between these weights and 1000 grains will be the weight of the body in grains. To find the weight of the water displaced by the body, transfer it to the basket at the bottom, and add weights

enough to the dish again to sink the instrument to the mark. The weights added will be the weight of the water displaced by the body. The specific gravity of the body will be its weight, divided by the weight of the water it displaces.

114. *Ordinary Hydrometers.* — These instruments are usually of the form shown in Figure 73. They are weighted at the lower end with mercury to keep them in an upright position. The bulb above the mercury causes them to displace enough of a liquid to float in it. When put in a liquid they sink in it till they displace their own weight. The deeper they sink in a liquid, the less its specific gravity. Their stems are graduated in such a way that the number on the stem at the surface of the liquid indicates the specific gravity of the liquid. This is a convenient, but not very accurate method of ascertaining the specific gravity of a liquid.

Fig. 73.



C. GASES.

115. *Expansibility of Gases.* — One of the most marked characteristics of a gas is its capacity for indefinite expansion. The tendency of a gas to expand may be illustrated by the following experiment. An india-rubber bag partially filled with air is closed air-tight and placed under the receiver of an air-pump. On exhausting the air from the receiver, the bag fills out, as shown in Figure 74.

The tendency of a gas to expand is due to two facts; namely, that the molecules of a gas are not held together by cohesion, and that they are moving rapidly in straight

lines. The condition of a gas in a closed vessel has been likened to that of a swarm of bees in a closed room, when all the bees are flying at random in straight lines. They would be constantly flying against each other and against the walls of the room. It has been calculated that the molecules of air are moving at the average rate of about 1600 feet a second. This velocity would be sufficient to carry a body in a vacuum some 40,000 feet, or about 7 miles high. Now the molecules of air in the rubber bag are all the time flying against each other and against the bag with this enormous velocity. They therefore tend to expand the bag. So long as there was air in the receiver outside the bag, the blows against the bag from within were met and balanced by an equal number of blows from without; but as the air was exhausted from the receiver, there were fewer and fewer blows upon the bag delivered by the molecules on the outside, and hence the bag began to yield to the more numerous blows from within.

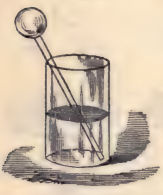
Fig. 74.

116. *The Diffusion of Gases.* — When any two gases are brought into contact, they rapidly mix with each other. This mixture of gases when brought into contact is called *diffusion.* This rapid diffusion of gases is due to the fact that the molecules are far apart and in constant motion. The molecules of the one gas quickly move into the spaces among the molecules of the other gas.

117. *The Expansive Power of a Gas increased by Heat.* — A bulb with a tube projecting from it is placed in a vessel of water so that the open end of the tube is under water, as shown in Figure 75. If the bulb is heated, the air in it will

expand so as to drive out a portion of it through the water. Heat always increases the expansive power of a gas.

Fig. 75.



This is because heat causes the molecules to fly about with greater velocity, and therefore with greater energy.

118. *The Expansive Power of a Gas increased by an Increase of Pressure.* — An increase of pressure on a gas increases its expansive power. This is because the increased pressure crowds the molecules nearer together, so that there are more molecules in the same space to beat against the inclosure. In the cylinder of the steam-engine, the steam is kept at a high temperature and under great pressure.

119. *The Three Gaseous Laws.* — *Equal volumes of all gases, at the same temperature and under the same pressure, contain the same number of molecules.* This is *Avogadro's law.*

The volume of a confined mass of gas varies inversely as the pressure to which it is exposed. The less the pressure the greater the volume, and the greater the pressure the less the volume. This is *Mariotte's law.* This law might be stated thus: the number of molecules of a gas in a given space, and the expansive power of the gas, vary directly as the pressure to which the gas is exposed.

The volume of a gas under constant pressure varies directly as the absolute temperature of the gas. This is *Charles's law.*

By *absolute temperature* is meant temperature measured from a point 459° below the ordinary zero. The temperature indicated by an ordinary thermometer may be converted into absolute temperature by adding 459° to it. Thus, a temperature of 70° on our scale would be a temperature of $70° + 459° = 529°$ on the absolute scale. A temperature of $-15°$ on our scale would be a temperature of $459° + (-15°) = 444°$ on the absolute scale.

120. The *Air-Pump.* — The essential parts of an *air-pump* are shown in Figures 76 and 77. There is a flat

Fig. 76.

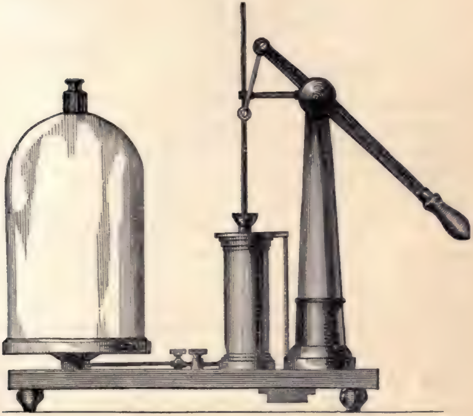
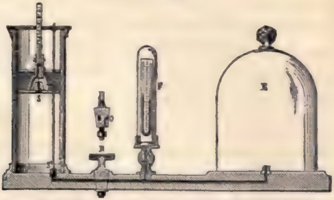


plate for holding the receiver *E*, called the pump-plate. It is ground perfectly flat, so that an *air-tight* joint is formed

Fig. 77.



between it and the receiver when the latter is placed upon it. A tube connects the pump-plate with the cylinder, in which a piston is moved up and down by means of the

handle. There is a little valve S in the piston, pressed down by a little spiral spring above it. There is also a valve S' at the bottom of the barrel, fastened to a rod which passes through the piston in such a way that the valve is opened when the piston rises, and closed when the piston is pushed down, by the friction of the rod against the piston. When the piston is drawn up the valve in the piston is closed, and no air can pass from above the piston into the space below it. At the same time S' at the bottom of the barrel is opened, and the expansive force of the air in the receiver E causes some of the air to pass out through the tube into the barrel below the piston. On pushing down the piston the valve S' is closed by the friction of the rod, and the valve S is opened by the expansive force of the air below it as the air becomes compressed, and the air in the barrel below the piston passes above it again. In this way, every time the piston is moved up and down, a part of the air is removed from the receiver. F is a gauge for showing the extent of the exhaustion; R is a cock, by means of which the receiver and the barrel may be put into communication with each other, or either may be shut off from the other and be put into communication with the external air. There is one opening straight through this cock, by means of which the receiver and barrel may be put into communication with each other, as shown in the lower part of Figure 77. There is another opening O, 90° from the former one, and communicating with the external air. When the cock is turned so that O is on the side of the receiver it will put it into communication with the external air; when O is turned so as to connect with the tube on the side of the barrel, it puts the barrel in communication with the external air.

There are many different forms of air-pumps; but with none of the ordinary pumps is it possible to obtain perfect exhaustion. The air becomes finally so attenuated

as not to have sufficient expansive force to open the valve.

121. *Sprengel's Air-Pump.* — When it is necessary to obtain a more perfect exhaustion than can be obtained by an ordinary air-pump, some form of a mercurial pump is employed. Figure 78 shows the simplest form of Sprengel's air-pump, and serves to illustrate the principle of all these mercurial air-pumps. An upright tube *c d*, some four or five feet in length, is connected at *c* by a short piece of rubber tubing to a funnel *A*, filled with mercury. The rubber tubing at *c* may be closed by means of a clamp, when the pump is not in operation. The bottom of the tube passes into a vessel *B*, into which it is fastened by a cork. The vessel *B* has a spout at the side, just a little above the lower end of the upright tube. The upright tube has a branch at *x*, by means of which it is connected with the receiver *R*, from which the air is to be exhausted. The mercury, being allowed to fall through the upright tube, carries by friction some of the air from the tube *x* down with it. The expansion of the air in the receiver brings fresh air into the tube as fast as it is removed by the falling mercury. The whole length of the tube from *x* down becomes filled with cylinders of mercury, separated by cylinders of air, all moving downward. The air and mercury escape from the spout at the side of the vessel *B*, and the mercury is caught in a basin, and from time to time poured back into the funnel *A*. As the exhaustion progresses, the air enclosed between the cylinders of mercury becomes less and less, and finally disappears entirely.

Fig. 78.

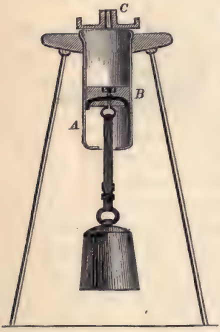
Sprengel's pump is only one of the many applications of the aspiratory effects of a current of air or of a liquid. Whenever

a current of air or of liquid passes through a gas, it carries some of the surrounding gas along with it, and so produces a partial exhaustion in its neighborhood, which occasions an inflow from all sides.

122. *Pressure of the Air.* — The pressure of the air may be illustrated by the following experiments. Place a small bell-jar, open at both ends, on the plate of the air-pump, and cover the top of the jar with the palm of the hand. When the air is exhausted from the jar, the hand is pressed firmly down upon the mouth of the jar. This is an illustration of the downward pressure of the air. It was not perceived at first, because the downward pressure of the air upon the hand was balanced by the upward pressure of the air within the jar.

The *weight-lifter* (Figure 79) serves to illustrate the upward pressure of the air. It consists of a cylinder of glass or metal, *A B*, with a piston moving up and down in it, air-tight. This cylinder is closed at the top by a plate *C*, to which may be screwed a tube to connect the cylinder with the air-pump. The cylinder is open at the bottom, and a heavy weight is fastened with a strap to the piston. If the air is exhausted from the cylinder above the piston, the piston and weight are raised by the upward pressure of the air acting upon the bottom of the piston.

Fig. 79.



Figures 80 and 81 represent two brass hemispheres, some four inches in diameter, the edges of which are made to fit tightly together. The whole can be screwed to the air-pump by means of the stop-cock at the bottom.

While the hemispheres contain air they can be separated with ease, since the outward pressure is just balanced by the inward pressure; but when the air within is pumped out, it is very hard to pull them apart. Since it is equally difficult to do this in whatever position the hemispheres are held, the experiment shows that the air presses in all directions.

Fig. 80.

Fig. 81.

This piece of apparatus is called the *Magdeburg hemispheres*, from Otto von Guericke, of Magdeburg, by whom it was invented.

The pressure of the air at the level of the sea is about 15 pounds to a square inch, or a ton to the square foot.

The surface of the body of a man of middle size is about 16 square feet; the pressure, therefore, which a man supports on the surface of his body is 35,560 pounds, or nearly 16 tons. Such enormous pressure might seem impossible to be borne; but it must be remembered that, in all directions, there are equal and contrary pressures which counterbalance one another. It might also be supposed that the effect of this force, acting in all directions, would be to press the body together and crush it. But the solid parts of the skeleton could resist a far greater pressure; and the cavities of the body are filled with air or liquids which exert a pressure outward equal to that of the external air. When the external pressure is removed from any part of the body, either by means of a cupping vessel

or by the air-pump, the pressure from within is seen by the distension of the surface.

123. *The Pressure of the Air decreases as we ascend above the Level of the Sea.* — The pressure of the air at the level of the sea is due to the downward pressure of all the layers of air above, transmitted throughout the mass below according to Pascal's law. Each layer of molecules of air is pulled downward by gravity, and transmits this pressure to all the layers below. Hence the pressure of a gas increases with the depth. It, however, increases more rapidly than the depth. For gases being compressible, as we descend in a gas the molecules are crowded more closely together, so that there are more molecules exerting pressure in each layer, and there are more layers in any given difference of depth.

D. Liquids.

124. *Compressibility of Liquids.* — For a long time it was thought that liquids were entirely incompressible. In the year 1661 some academicians of Florence, wishing to find whether water was compressible, filled a thin globe of gold with that liquid, and, after closing the orifice perfectly tight, subjected the globe to great pressure, with a view of altering its form, knowing that any alteration of form would occasion a diminution of capacity. They failed to compress the water, but discovered the porosity of gold, for the water forced its way through the pores of the globe, and stood on the outside like dew.

Fig. 82.

In more recent times it has been shown that liquids are slightly compressible. The apparatus for measuring the com-

pressibility of a liquid is shown in Figure 82. It consists of a strong glass cylinder within which there is a long glass bulb A, from which proceeds a fine bent tube, with its end dipping under the mercury in the bottom of the cylinder at O. The liquid to be tested is introduced into the bulb A so as to fill both it and the tube. The cylinder is then filled with water through the funnel R, and pressure applied by means of the thumb-screw P, which forces a piston down upon the water. The rise of the mercury in the fine tube shows the amount of the compression of the liquid in the bulb. For a pressure of one atmosphere, or 15 pounds to the square inch, the volume of water is diminished about 5 parts in 100,000. At the depth of a mile, the volume of sea-water is diminished 1 part in 130.

In liquids, as in gases, elasticity is developed only by compression, but their elasticity is perfect. No matter to what pressure a liquid has been subjected, it will return to exactly its original volume as soon as the pressure is removed.

125. *The Tendency of Liquids to assume a Globular Form.* — When left to itself, a liquid always assumes a globular form. This is because all the molecules, as they work their way through the mass, are stopped by the force of gravity and cohesion at the same distance from the centre of the mass. The tendency of the molecules of liquids to collect into spheres may be shown by the following experiment. Prepare a mixture of water and alcohol which shall be just as heavy as sweet-oil, bulk for bulk, and introduce some of the oil carefully into the centre of this mixture by means of a dropping-tube; the oil will neither rise nor sink, but gather into a beautiful sphere.

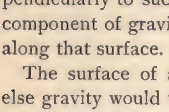
Rain-drops, dew-drops, and the manufacture of shot illustrate this tendency of the molecules of liquids. In the manufacture of shot, melted lead is poured through a sieve at the top of a very high tower, and the drops in falling take the form of spheres, which become solid before they reach the bottom.

126. *The Free Surface of a Liquid at Rest is a Level Surface.* — A level surface is one along which gravity does not tend to produce any motion. Gravity always acts perpendicularly to such a surface, and hence there can be no component of gravity which would tend to produce motion along that surface.

The surface of a liquid at rest must be a level surface, else gravity would tend to move the liquid along the surface, and the liquid could not remain at rest.

Thus, in Figure 83, if the surface of the liquid were not level, the force of gravity acting upon the particle M would be decomposed into two components, — one perpendicular to the surface which would produce pressure, and one along the surface which would produce motion.

Fig. 83.



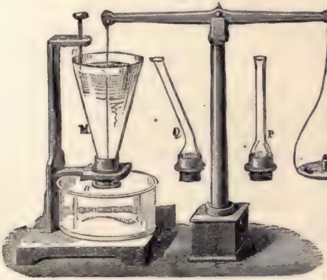
127. *The Downward Pressure of a Liquid due to Gravity is proportional to the Depth.* — Since the downward pressure of a liquid due to gravity at any point is the pressure that has been transmitted to that point by the layers of molecules above, the pressure at that point will be proportional to the number of layers of molecules above the point; and since liquids are practically incompressible, the number of layers of molecules will be proportional to the depth.

The amount of pressure transmitted to the layers below by any layer of molecules is entirely independent of the extent of the layer. For if the upper layer consisted of a single molecule, it would exert the pressure of a molecule upon the surface of a molecule, and that pressure would be transmitted to every equal surface below. If the upper layer consisted of 5 molecules, they would exert a pressure of 5 molecules upon a surface of 5 molecules, which would be the pressure of one molecule to the surface of one molecule as before. Hence the pressure at any point in a

vessel containing a liquid does not depend at all upon the size and shape of the vessel, but simply upon the depth of the point below the surface.

128. *Pascal's Vases.*—The fact that the pressure of a liquid upon a given surface depends upon the depth of the liquid only, and not upon the size or shape of the vessel which contains the liquid, may be illustrated by means of *Pascal's vases* (Figure 84). The vessels *M*, *P*, and *Q* may in turn be screwed into the plate *c*. A disc *a* suspended from one end of the beam of a balance with a thread, and

Fig. 84.



held up by weights at the other end of the beam, serves as the bottom of the vessel, which it closes water-tight. Water is poured carefully into the vessel *M* till its depth is just sufficient to displace the plate *a*, and the height of the water is marked by the point *o*. *M* is then removed, and *P* and *Q* are in turn put into its place. It will be found that each will have to be filled to exactly the same height to displace the plate *a*.

It follows from the above that a very small quantity of water can produce considerable pressure. Let us imagine a cask, for example, filled with water, and having a long narrow tube tightly fitted into its top. If water

is poured into the tube, there will be a pressure on the bottom of the cask equal to the weight of a column of water whose base is the bottom itself, and whose height is equal to that of the water in the tube. The pressure may be made as great as we please; by means of a mere thread of water forty feet high, Pascal succeeded in bursting a very solidly constructed cask.

129. *The Upward Pressure of a Liquid.* — The downward pressure of a liquid at any point must be balanced by an equal upward pressure, according to the law that action and reaction are always equal and opposite.

The following experiment (Figure 85) serves to show the upward pressure of liquids. A large open glass tube *A*, one end of which is ground, is fitted with a ground-glass disc *O*, or still better with a thin card or piece of mica, the weight of which may be neglected. To this is attached a string *C*, by which it can be held against the bottom of the tube. If the whole is then immersed in water, the disc does not fall, although no longer held by the string; it is consequently kept in its position by the upward pressure of the water. If water is now slowly poured into the tube, the disc will sink only when the height of the water inside the tube is equal to the height outside.

Fig. 85.

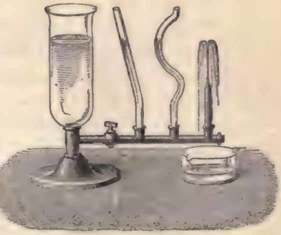
130. *The Pressures of different Liquids at the same Depth are proportional to their Densities.* — The pressure at the same depth would be about 12½ times as great in mercury as in water, and about .8 as great in alcohol as in water. This is owing to the fact that, mercury being about 12½ times as dense as water, each layer of mercury would transmit downward 12½ times as much pressure as a layer of the same thickness of water; and a layer of alcohol, .8 times as much.

131. *The Pressure is the same at every Point in a Horizontal Layer of a Liquid at Rest.* — Owing to the extreme mobility of liquids, it would be impossible for a liquid to remain at rest if at any point in it the pressures acting upon that point from all directions were not equal or balanced. If the upward or downward pressure at any point were not balanced, a particle at that point would tend to move up or down as the case might be. If the pressure were not the same throughout a horizontal layer, there would be some point in the horizontal layer where the horizontal pressures to the right and left would not be balanced, and a particle at that point would move in the direction in which it was urged by the larger pressure; that is, the liquid would not be at rest. This is true of all fluids, both liquids and gases.

Any disturbance of the equilibrium of pressure in horizontal layers gives rise to currents which will flow towards the region of low pressure till the equilibrium is restored.

132. *Rise of Liquids in Communicating Vessels.* — When a liquid is contained in vessels which communicate with each other and is at rest, it will be found to stand at the same height in all the vessels, whatever may be their size or shape. Thus, in Figure 86 the water stands at the same height in all the tubes as in the large vessel. If one of the tubes is cut off below the level of the water in the other vessels, and drawn out to a narrow mouth, the liquid will spout out of this tube nearly to the height of the liquid in the others. The rise of a liquid to the same height in a series of communicating vessels is

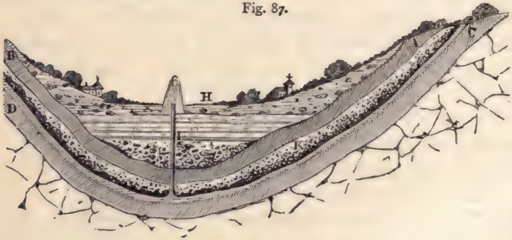
Fig. 86.



due to the fact that when a liquid is at rest, the pressure must be the same throughout each horizontal layer. Each horizontal layer of the water taken through all the vessels must then be the same distance below the free surface of the liquid in each vessel. Hence these free surfaces must be in the same horizontal line, or at the same level.

The tendency of liquids to find their own level is very important, and of continual application. When any system of pipes, however complicated, is connected with a reservoir, the water will rise in every pipe to the level of the water in the reservoir.

Fig. 87.



133. *Springs and Artesian Wells.* — All natural collections of water illustrate the tendency of a liquid to find its level. Thus, the Great Lakes of North America may be regarded as a number of vessels connected together, and hence the waters tend to maintain the same level in all. The same is true of the source of a river and the sea, the bed of the river connecting the two like a pipe.

Springs illustrate the same fact. The earth is composed of layers, or *strata*, of two kinds: those through which water can pass, as sand and gravel; and those through which it cannot pass, as clay. The rain which falls on high ground sinks through the soil until it reaches a layer of this latter kind, and along this it runs until it finds some opening through which it flows as a spring.

It is the same with *Artesian wells*. These wells derive their name from the province of Artois in France, the first part of Europe where they became common. It would seem, however, that wells of the same kind were made in China and Egypt, many centuries earlier.

In Figure 87, suppose *A B* and *C D* to be two strata of clay, and *K K* to be a stratum of sand or gravel between them. The rain falling on the hills on either side will filter down through this sand or gravel, and collect in the hollow between the two strata of clay, which prevent its escape. If now a hole is bored down to *K K*, the water, striving to regain its level, will rise to the surface at *H*, or spout out to a considerable height above it.

Sometimes the water between two such impervious strata makes its way to the surface through some fissure in the upper stratum, constituting a deep-seated spring.

Fig. 88.

134. *The Water-Level.* — The water-level (Figure 88) is constructed on the principle that water will rise to the same level in two communicating vessels. It consists of a metal tube *b* bent at right angles at its extremities. It carries at each end a glass tube *a* of the same size. The tube is supported on a tripod stand. It is first placed in a nearly horizontal position, and then some colored water is poured into the glass tube *a*. The water rises to the same level in both the glass tubes. The line of sight *m n*, which just grazes the two surfaces, will be a horizontal line.

135. *The Spirit-Level* — The operations of levelling are

effected much more easily and accurately by means of an instrument called the *spirit-level.*

It consists of a closed glass tube, *A B* (Figure 89), with a slight upward curvature. It is filled with spirit, except a bubble of air which tends to rise to the highest part of the tube. It is set in a case *C D*, and when this is placed on a perfectly level surface, the bubble is exactly in the middle of the tube, as in the figure.

Fig. 89.

136. *Rise of two Different Liquids in Communicating Vessels.*—If into one of two communicating tubes (Figure 90) we pour any liquid, as mercury, it will rise to the same height in both branches. If now we pour water into one of the tubes, the mercury will rise somewhat in the other, but not nearly so high as the water. The height of the two liquids above the surface of separation will be in the inverse ratio of the densities of the liquids. This will be true in all cases. This is because the pressures of the two liquids at the surface of separation must be equal, so as to balance each other. Now the downward pressure of the water at the surface of the mercury is due to the depth of the water above it, and the upward pressure of the mercury at the same point is due to the depth of the mercury above the level of this surface in the other tube; and to have these pressures equal, these depths must be in the inverse ratio of the densities of the liquids.

Fig. 90.

137. *Capillarity.* — The rise of liquids in communicating vessels is modified in a remarkable manner when any of the communicating vessels are very narrow. Such narrow vessels and fine tubes are called *capillary*, from the Latin *capillus*, a hair. The action of such tubes upon the rise of liquids within them is called *capillary action*. This action is not, however, confined to the cases of fine tubes; but when the containing vessel is wide, the action extends only a short distance from the sides of the vessel. The free surface of a liquid in a wide vessel is not horizontal in the neighborhood of the sides of the vessel, but presents a very decided curvature. When the liquid wets the vessel, as in the case of water in a glass vessel (Figure 91), the

Fig. 91. Fig. 92.

Fig. 93.

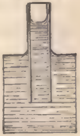


Fig. 94.

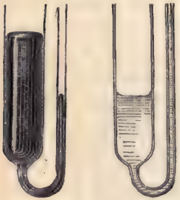
surface of the liquid near the glass is *concave*. When the liquid does not wet the vessel, as in the case of mercury in a glass vessel (Figure 92), the surface near the glass is *convex*.

When a narrow tube of glass is plunged into water or any other liquid that will wet it (Figure 93), the liquid rises higher within the tube than on the outside, and the column of the liquid within the tube will be *concave* at the top. In this case there is a *capillary ascension* which varies in amount with the diameter of the tube and the nature of the liquid. The finer a tube, the higher the liquid will rise in it. If a glass tube is plunged in mercury, which does not wet it, the mercury will fall within the tube below the level of the mercury outside (Figure 94),

and the top of the column of mercury within the tube will have a *convex* surface. In this case there is a *capillary depression*. The finer the tube, the greater the depression.

If we take two bent tubes, each having one branch of considerable diameter, and the other extremely narrow, and pour water into one of the tubes, and mercury into the other, the water will stand higher in the capillary than in the principal branch, and the mercury will stand lower in the capillary branch (Figure 95). The free surface will be concave in both branches in the case of water, and convex in the case of mercury. Capillary action is manifested whenever the surface of a liquid comes in contact with a solid. If a clean glass plate is dipped into water, the water will rise a little on each side of the plate. If the same plate is dipped in mercury, the mercury will be depressed a little on each side of the plate. Capillary action is also often manifested when the surfaces of two liquids are brought into contact by the peculiar movements which take place.

Fig. 95.



138. *Illustrations of Capillarity.* — A lamp-wick is full of tubes and pores, and capillary force draws the oil up through these to the top of the wick, where it is burned. When one end of a cloth is put into water, capillary force draws the water into the tubes and pores of the cloth, and the whole soon becomes wet. In the same way any other porous substance soon becomes wet throughout, if a corner of it is put into water. Blotting-paper is full of pores into which the capillary force draws the ink. The use of a towel for wiping anything which is wet depends on the same principle.

139. *Strength of the Capillary Force.* — It is well known

that when a piece of cloth is wet, it is almost, if not quite, impossible to wring or squeeze it dry. This shows that the capillary force which holds the water in the pores of the cloth is very strong. Some solids, as wood, swell on becoming wet. If holes are drilled into a granite rock, and dry wooden plugs driven into them, and water is then poured over the ends of the plugs, the capillary force draws the water into the wood, which swells and splits the rock. This is a striking illustration of the strength of the capillary force.

140. *Capillary Force never causes a Liquid to flow through a Tube.* — If a glass tube is so fine that the capillary force will draw water into it to the height of two inches, and the tube is then lowered so that not more than half an inch shall be above the surface of the water, the water will not overflow the tube. If, however, the water is removed as soon as it comes to the top, more will rise in the tube to take its place.

When a lamp is burning, the oil is passing up continually through the wick, because it is burned as soon as it reaches the top; but when the lamp is not burning the oil does not overflow the wick.

Fig. 96.

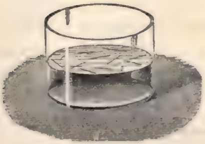
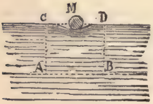


Fig. 97.

141. *Heavy Bodies floating on Water by Capillary Action.* — According to Archimedes's principle, a body cannot float on a liquid unless it is less dense than the liquid. This seems to be contradicted by certain well-known facts. Small steel needles will float on water when placed carefully on the surface (Figure 96). Several insects walk on water (Figure 97), and many

heavy bodies can, if sufficiently minute, float on the surface of water. In all these cases the bodies are not *wet* by the liquid, and consequently depressions are formed around them by capillary action, as shown in Figure 98. The liquid displaced by one of these bodies is really equal to that which would fill the whole depression, or the space below the dotted line *C D* (Figure 98), and this liquid would in every case be equal to the weight of the floating body.

Fig. 98.



142. *Endosmose.* — If a vessel *v* (Figure 99), closed below by a thin membrane *b a*, and terminating above in a long tube, is filled with a solution of gum in water, and immersed in water, the liquid will slowly rise in the tube till it reaches a certain point *n*. At the same time traces of gum will be found in the water outside. The water passes in through the membrane and mixes with the solution on the inside, while some of the gum passes out through the membrane and mingles with the water outside. The rise of the liquid in the tube shows that the water passes in faster than the gum passes out. Similar results would be obtained if water holding albumen, sugar, or gelatine in solution were employed in the small vessel, or if the membrane were replaced by a slab of wood or porous clay. The passage of two liquids through a membrane or porous substance which separates them is called *endosmose*. There are two currents of different volumes which flow, through the membrane in opposite directions. Sometimes the term *endosmose* is applied to the more abundant flow, and the term *exosmose* to the less abundant flow. The phenomena of endosmose are somewhat akin to those of capillarity.

Fig 99.

Substances have been divided into two classes as regards their power of passing through porous diaphragms, namely, into *crystalloids* and *colloids*. The former are susceptible of crystallization, form solutions free from viscosity, are sapid, and have great powers of diffusion through porous septa. The latter,

including gum, starch, albumen, etc., are characterized by a remarkable sluggishness and indisposition both to diffusion and to crystallization, and when pure are nearly tasteless.

143. *Rise of Liquids in Exhausted Tubes.* — Since the atmosphere presses 15 pounds to the square inch upon the surface of a liquid, if this pressure is removed or lessened at any point on the surface, the liquid will tend to rise at that point. If a long glass tube, open at both ends, is connected at the top by means of a rubber tube with an air-pump, and is held upright with its lower end under the surface of mercury, when the pump is worked the mercury will begin to rise in the tube, and it will rise higher and higher as the exhaustion continues. Were a tube over 30 inches long connected with a Sprengel air-pump so as to secure a more perfect exhaustion, the mercury would rise about 30 inches in the tube. Under similar circumstances water would rise about 33 feet high. In each case the liquid would rise in the tube till the pressure within the tube at a level with the surface of the liquid outside was equal to the pressure of the air on the surface of the liquid, or about 15 pounds to the square inch. The height to which different liquids will rise in exhausted tubes will be in the inverse ratio of the densities of the liquids.

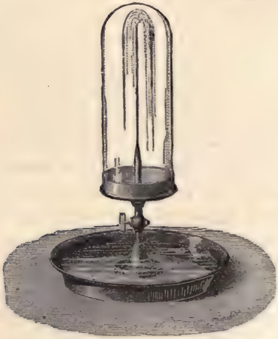
In drinking lemonade through a straw, the air is first drawn out of the straw by the mouth, and the liquid is forced up through the straw by the pressure of air on the surface. When a jar is filled with a liquid and then inverted with its mouth under the same liquid in a vessel, the pressure of the air on the surface of the liquid in the vessel will keep the liquid up in the jar.

That it is the pressure of the atmosphere on the surface of the liquid in the vessel that keeps the liquid up in the jar may be shown by the following experiment. Fill a jar with mercury, invert it, and place its mouth under some

mercury in a dish. Place the jar thus inverted in the dish of mercury under the receiver of an air-pump, and exhaust the air. As the exhaustion proceeds, and the pressure of the air upon the surface of the mercury becomes less and less, the mercury falls in the jar.

144. *The Fountain in Vacuo.* This apparatus is an illustration of the tendency of liquids to rise in exhausted

Fig. 100.

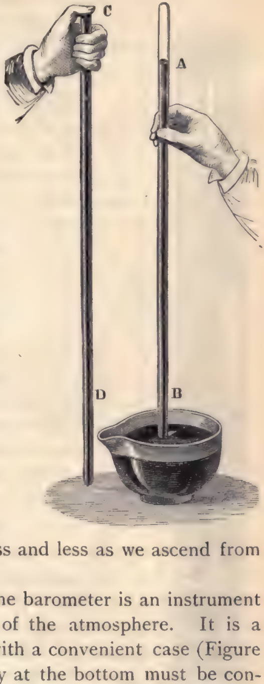


vessels (Figure 100). It consists of a bell-jar, provided with a tube and stopcock at the bottom. The bell-jar is first exhausted by means of the air-pump. The stopcock is then closed, and the bell-jar is removed to a vessel of water. After the end of the tube has been placed under water the stopcock is again opened. The pressure of the air on the surface of the water in the vessel drives the water up in the bell-jar in a jet so as to form a beautiful fountain.

145. *Torricelli's Experiment.* — Torricelli took a glass tube somewhat more than 30 inches long and closed at one end, and filled it with mercury. He then closed the tube with his thumb, and inverted it in a dish of mercury (Figure 101). On opening the tube under the mercury,

he found that the mercury fell in the tube till the top of the column *A* stood about 30 inches above the surface of the mercury in the dish. Such a tube is called a *Torricellian tube*, and the space above the column of mercury in the tube is called a *Torricellian vacuum*.

Fig. 101.



146. *Pascal's Experiment.* — Pascal had a Torricellian tube taken from the bottom to the top of a mountain, and ascertained that the column of mercury in the tube fell as the ascent progressed. He therefore concluded that the mercury was kept up in the tube by the pressure of the atmosphere on the surface of the mercury in the vessel, since the pressure would necessarily become less and less as we ascend from the level of the sea.

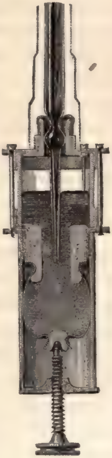
147. *The Barometer.* — The barometer is an instrument for measuring the pressure of the atmosphere. It is a Torricellian tube furnished with a convenient case (Figure 102). The vessel of mercury at the bottom must be constructed so as to prevent the spilling of the mercury in transportation, and so as to allow the atmosphere to act freely upon the mercury.

One of the best forms of the cistern for holding the mercury is shown in Figure 103. The upper part of the cistern is a cylinder of glass, the middle part is a cylinder of box-wood,

and the bottom of the cistern is of leather, and may be raised or lowered by means of the screw below. The top of the cistern is mainly of wood, but just around the tube where it enters the cistern is a piece of leather, fastened firmly to the neck of the tube and to the collar of the wooden cup. This leather serves the double purpose of preventing the mercury from escaping when the barometer is inverted, and of allowing the air free access through its pores to the mercury in the cistern. When the barometer is in use, the screw at the bottom of the cistern must be so adjusted that the free surface of the mercury will just touch the ivory point seen at the right; when the barometer is in transportation, the screw at the bottom is turned up till the mercury presses against the top of the cistern.

Fig. 102.

Fig. 103.

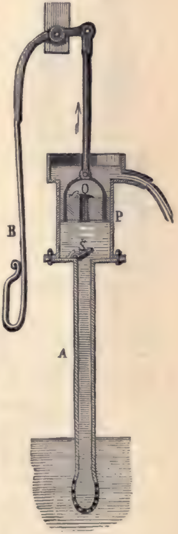


148. *Use of the Barometer in measuring the Height of Mountains.* — One of the chief uses of the barometer is to measure the height of mountains. It has already been stated that the atmospheric pressure is less as the height above the earth is greater. When we have found at what rate it diminishes, we can readily find the height of mountains by means of the barometer. We have to find the difference between the readings of the barometer at the level of the sea and at the top of the mountain. This shows how much the pressure has diminished, and from this we can find the height of the mountain.

If the pressure of the atmosphere decreased uniformly as we ascend, it would be very easy to find the elevation of a place by means of a barometer. But, owing to the variations in the density of the air as we ascend, the pressure changes according to a complicated law; and this complicates the formula for finding the exact elevation of a place from the readings of the barometer. As a rough rule, it may be stated that the barometer falls one inch for every 900 feet of ascent.

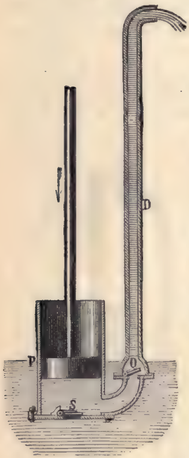
149. *Suction-Pump.* — The suction-pump consists of a cylinder, or barrel, at the top of a pipe *A* (Figure 104), communicating with the water in the reservoir. A piston *P* is moved up and down in the barrel by means of the handle *B*. There is a valve *S* at the top of the tube leading into the reservoir, and another valve *O* in the piston. Both valves open upward. The pump first exhausts the air from the pipe. As the air is exhausted, the water is driven up through the pipe and finally into the pump-barrel by the pressure of the air on the surface of the water in the cistern. Every time the piston is pushed down, the valve *S* closes, and keeps the water in the barrel from passing back into the cistern; at the same time the valve in the piston opens, and allows the water in the barrel below it to pass above it. When the piston is raised, the valve *O* closes, and keeps the water above it from passing below it; at the same time the valve *S* is forced open by the pressure from below, and the water

Fig. 104.



rushes up through it to fill the barrel behind the piston. As the piston is raised, the water above the piston passes out by the discharge-pipe at the top of the barrel. With this pump the water is raised into the barrel by the atmospheric pressure, and is then lifted out of the barrel by the piston. Hence with the suction-pump water can be raised only about 30 feet high.

Fig. 105.



150. *Force-Pump.* — The simple *force-pump* is shown in Figure 105. The piston P is solid. The discharge-pipe D communicates with the bottom of the cylinder, and has a valve O in it opening upward. There is also a valve S in the bottom of the barrel, also opening upward. When the plunger is raised, the valve O closes, and the water rushes into the cylinder through the valve S; when the plunger is pressed down, the valve S closes, and the water is forced out through the valve O into the discharge-pipe. The only limit to the height to which water may be raised by means of this pump is that of the power used and of the strength of the pump.

The force-pump and the suction-pump may be combined, as shown in Figures 106 and 107; that is to say, the cylinder of the force-pump may be at the top of a pipe about 30 feet above the surface of the water to be raised.

151. *The Air-Chamber.*—The *air-chamber* is a device by which the water from a force-pump may be made to escape in a continuous and forcible stream. It consists of an air-tight box C above the valve O in the discharge-pipe (Figures 105 and 108). The pipe D passes nearly

to the bottom of the chamber. When the pump is working, the water is forced into the air-chamber through the valve *O*. As soon as the end of the pipe *D* is covered, the air in the upper part of the chamber begins to be compressed. The compression increases the elastic force of the air, and causes it to press steadily and forcibly on the surface of the

Fig. 106.

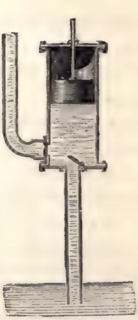


Fig. 107.

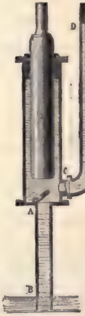
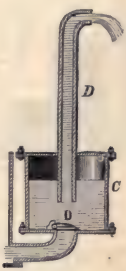


Fig. 108.

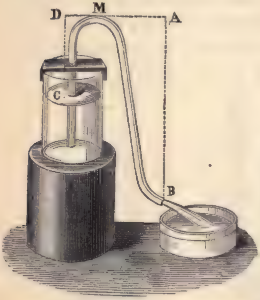


water. This steady pressure forces the water out through the pipe *D* in a steady stream. If *D* ends in a narrow nozzle, the water will be obliged to pass through it very rapidly to escape from the chamber as rapidly as it is pumped into it. In this way a stream may be obtained of sufficient force to be thrown a great distance, as in the fire-engine.

152. *The Siphon.* — The *siphon* is used for transferring liquids from one vessel to another. It consists of a bent tube *C M B* (Figure 109), with arms of unequal length. The air must be removed from the tube in the first place, either by applying the mouth to the end *B*, after the other arm of the siphon has been introduced into the vessel of water, or by filling the siphon with water before it is placed in the vessel.

The water will flow through the siphon from C to B until the vessel is emptied, or until the level of the water falls below the mouth of the arm in the vessel. The flow of the liquid through the siphon seems opposed to the well-known fact that water will not run up hill. But notwithstanding this seeming inconsistency, it will be seen that the water is flowing from a higher level C to a lower level B. If we consider a layer of water in the siphon at M, we see that the force which acts upon it from left to right is equal to the pressure of the atmosphere minus the pressure of the water in the tube from M to C, whose depth is $D\ C$; and the pressure which acts upon it from right to left is equal to the pressure of the atmosphere minus the pressure of the water in the tube from M to B, whose depth is $A\ B$. Since $A\ B$ is greater than $D\ C$, the pressure at M towards the right will be greater than that towards the left. Consequently, the water at M moves on towards B, and as it moves away more water is driven up into the arm $C\ M$ to take its place by the pressure of the atmosphere on the surface of the water in the vessel. No liquid will flow through a siphon unless the atmospheric pressure is sufficient to raise it to the bend of the tube.

Fig. 109.



153. *Tantalus's Cup.* — This is a glass cup, with a siphon tube passing through the bottom, as shown in Figure 110. If water is poured into the cup, it will rise both inside and outside the siphon until it has reached the top of the tube, when it will begin to flow out. If the

water runs into the cup less rapidly than the siphon carries it out, it will sink in the cup until the shorter arm no longer dips into the liquid, and the flow from the siphon ceases. The cup will then fill, as before; and so on.

Fig. 110.

In many places there are springs which flow at intervals, like the siphon in this experiment, and whose action may be explained in the same way. A cavity under ground (Figure 111) may be gradually filled with water by springs, and then emptied through an opening which forms a natural siphon. In some cases of this kind the flow stops and begins again several times in an hour.

Fig. 111.

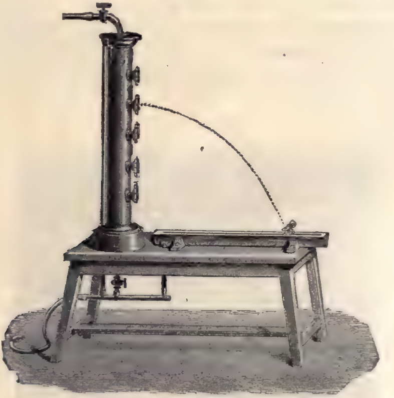
154. *Efflux of Liquids.* — If an opening is made in the side of a vessel containing water, the liquid escapes from the opening with a velocity which increases with the depth of the orifice below the surface of the water in the vessel. The height of the water above the orifice is called the *head* of the water. Torri-

celli arrived, by experiment, at the conclusion that the velocity of efflux is equal to that which a body would acquire by falling freely from the surface of the water to the centre of the orifice. If the height of the surface of the water above the centre of the orifice is represented by h, the velocity of efflux would be given by the formula

$$V = \sqrt{2gh}.$$

It is assumed that the sides of the vessel are thin, and that the diameter of the orifice is very small compared with that of the vessel. The jet issuing from the orifice is *parabolic*. By measuring its range, we can calculate the velocity of efflux.

Fig. 112.

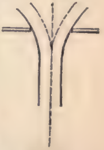


An apparatus for measuring the range of the jet is shown in Figure 112. It consists of a cylinder, in which are a number of equidistant orifices in the same vertical line. A faucet above supplies the cylinder with water, and with the help of an overflow-pipe keeps the water at a constant level, which is as much above the highest orifice as each orifice is above that next below it. The liquid which escapes is received in a trough, the edge of which is graduated. A travelling-piece, carrying a disc

with a circular aperture in its centre, slides along the trough. The travelling-piece is placed so that the jet from any orifice passes through the centre of the aperture in the disc. The range of the jet is then indicated on the edge of the trough.

It is found, by experiment, that the quantity of water discharged from a circular orifice is less than would be obtained by multiplying the size of the orifice by the velocity of discharge. This is because the particles of liquid at the margin of the orifice have a converging motion, in consequence of which the jet contracts rapidly for a short distance from the orifice (Figure 113). The portion of the jet at the end of this contraction is called the *vena contracta*, or contracted vein. Its section is about .6 that of the orifice. If the quantity of discharge is calculated by multiplying the section of the *vena contracta* by the velocity of efflux, the result agrees with experiment.

Fig. 113.



If the liquid is discharged through a cylindrical tube a few inches long, of the same section as the orifice, it will be found by measurement that the velocity has decreased somewhat, but the amount of discharge obtained by calculation will agree with that ascertained by experiment. The adhesion of the water to the sides of the tube prevents the contraction of the vein, and also diminishes the velocity of the jet by friction.

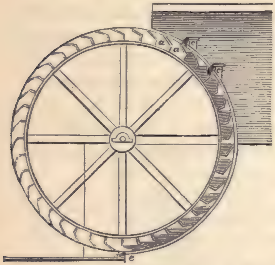
When the liquid flows through a long tube, the velocity is considerably reduced by the friction of the molecules against each other, and against the sides of the tube. The velocity is also least at the sides of the tube, and greatest at the centre.

155. *Water-Wheels.* — One of the most important sources of mechanical power is that of falling water. The falling or running water is made to turn a wheel called a *water-wheel;* and this wheel, by means of bands or gearing, is made to work almost any kind of machinery.

Water-wheels are of various forms. Some turn on an upright axis, and others on a horizontal axis. The latter are called *vertical water-wheels*, and the former *horizontal water-wheels*.

One of the most common of vertical water-wheels is represented in Figure 114. It consists of a series of boxes, or *buckets*, arranged on the outside of a wheel or cylinder. Water is allowed to flow into these buckets on one side of the wheel, and by its weight causes the wheel to turn. The buckets are so constructed that they hold water as long as possible while they are going down, but allow it all to run out before they begin to rise on the other side.

Fig. 114.



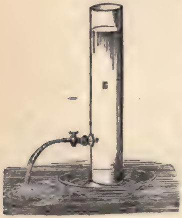
A wheel like this is called a *breast-wheel.*

The *overshot* wheel is similar to the breast-wheel in all respects, except that the water is led over the top of the wheel, and poured into the buckets on the other side.

The *undershot* wheel has boards projecting from its circumference, like the paddle-wheel of a steamboat. The water runs under the wheel, and turns it by force of the current pressing against the boards.

156. *The Hydraulic Tourniquet.* — If a vessel *E* (Figure 115), having a spout and faucet on one side, is filled with water and floated in a dish on water so as to move easily, on opening the faucet so as to allow the water to escape, the vessel will begin to move backward. This is due to the reaction of the water against the back of the vessel. While the faucet was closed, the pressure of the water against the front of the vessel at the orifice balanced the pressure of the

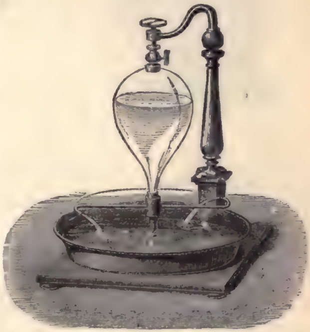
Fig. 115.



water against the back of the vessel at the same point. But when the faucet is open, there is no pressure against the front of the vessel to balance the reaction of the water against the back of the vessel; hence the backward motion of the vessel while the latter is escaping.

The *hydraulic tourniquet* (Figure 116) consists of a vessel capable of rotating on a vertical axis. Two tubes project from the bottom of the vessel in opposite directions. The ends of these tubes are open, and are bent round in opposite directions. As the water escapes from these tubes, the vessel is put into rapid rotation by the reaction of the water against the parts of the tubes opposite the openings.

Fig. 116.



157. *Turbine Wheel.*—One form of the *turbine wheel* is shown in Figure 117. This wheel turns in a horizontal plane. The buckets are placed in the outer part of the wheel, which is free to turn on a vertical axis. The curved partitions, or *guides*, within the wheel are stationary. These partitions are placed at the bottom of a long cylinder, into which the water is admitted by the pipe. The partitions are curved, so as to direct the water against the buckets at the most advantageous angle. The water is discharged at the rim of the wheel. Figure 118 is a section of a turbine wheel. The buckets are represented in the outer portion, and the guides in the inner circle.

There are many kinds of turbines, and their effective

Fig. 117.

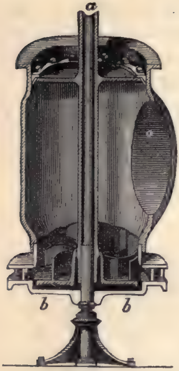


Fig. 118.

power is from 75 to 88 per cent of that in the acting body of water. In the best form of overshot and breast wheels, it is from 65 to 75 per cent, and in undershot wheels from 25 to 33 per cent.

E. Solids.

158. *Tendency of Solids to assume a Crystalline Structure.*— Solids, as a rule, tend to assume a crystalline structure. This tendency is best shown by allowing a substance to pass gradually from a liquid to a solid state. Place a rather dilute solution of acetate of lead in a tank with parallel sides of glass (such as are often used for projection), and fix two platinum wires in the solution, about an inch apart. Place the tank before the condenser of a magic lantern, and focus the wires on the screen. Connect the wires with the poles of a small voltaic battery. The lead will separate from the solution, and collect as a solid upon the wire connected with the negative pole of the battery. Beautiful fern-like forms will be seen to grow up on the screen. These forms are the crystals of lead. As the substance passes slowly from the liquid to

the solid state, the molecules are free to arrange themselves according to their tendencies.

If alum is added to hot water as long as it will dissolve, and then the water is allowed to cool slowly, a part of the alum will be deposited on the bottom of the dish, — not in a confused mass, but in beautiful crystals. If saltpetre, nitrate of baryta, or corrosive sublimate is treated in the same way, beautiful crystals will be formed, but in each case the crystals will have a different shape.

Melt some sulphur in a crucible, and allow it to cool slowly till a crust forms on the surface; then carefully break the crust and pour off the remaining liquid, and the crucible will be found lined with delicate needle-shaped crystals (Figure 119).

Fig. 119.

Large crystals of many solids can be obtained by dissolving as much of the solid as is possible in cold water, and then setting it away in a shallow dish where it will be free from dust and disturbance, and allowing the water to evaporate very slowly. The more gradual the formation, the larger are the crystals. The larger crystals seen in cabinets of minerals were probably centuries in forming. The water in which the solid was dissolved found its way into a cavity of a rock, and there slowly evaporated.

The tendency of the cohesive force to form the molecules into crystals is strikingly shown in cannon which have been many times fired, and in shafts of machinery and axles of car-wheels which are continually jarred. Such bodies often become brittle, and on breaking show the smooth faces of the crystals which have been formed. The continued jarring gives the molecules a slight freedom of motion, and crystals are slowly built up.

Many solids are crystalline in structure which do not

appear to be so. Thus, a piece of ice is a mass of the most perfect crystals, but they are so closely packed together that we cannot readily distinguish them.

159. *Properties of Solids.* — A body is said to be *tenacious* when it is difficult to pull it in two. All solids are more or less tenacious, but they differ greatly in the degree of their tenacity. A body is said to be *hard* when it is difficult to scratch or indent it, that is to say, when it is difficult to displace its molecules. All solids are *elastic* within certain limits, and this elasticity may be developed by stretching, by bending, by twisting, and by compression, that is, by any kind of strain whatever. Different solids, however, differ greatly in the limit of their elasticity. When the strain is carried beyond the limit of elasticity, the body must either break or take up permanently a new form. A body which is apt to break when strained beyond the limit of elasticity is said to be *brittle.* A brittle substance is not always *easily* broken. Such a body will not break unless strained beyond the limit of its elasticity, and that is often a difficult thing to do. It is not easy to break a glass rod an inch in diameter, yet glass is the most brittle substance known. Substances which can readily take permanently new forms are said to be *malleable* or *ductile.* A malleable substance is one that can be hammered or rolled into sheets, and a ductile substance one that can be drawn into wire. All malleable substances are to some extent ductile, but the most malleable are not the most ductile.

Gold is one of the most malleable of the metals. In the manufacture of gold-leaf, it is hammered out into sheets so thin that it takes from 300,000 to 350,000 of them to make the thickness of a single inch.

The gold is first rolled out into sheets by passing it many times between steel rollers in what is called a rolling-machine. The rollers are so arranged that they can be

brought nearer to each other, pressing the gold into a thinner and thinner sheet every time it is passed between them. After it has thus been rolled out to the thickness of writing-paper, it is cut up into pieces about an inch square. These are piled into a stack with alternate pieces of tough paper, and beaten with wooden mallets. They are again cut up into small pieces, and arranged in a stack with alternate squares of gold-beater's skin, and again beaten with mallets. This last process is usually repeated three times.

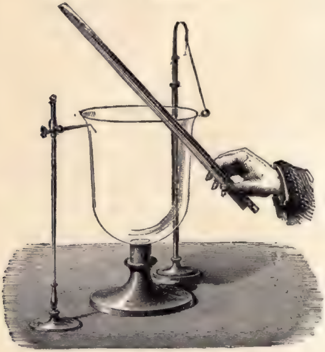
II.

SOUND.

A. Origin.

160. *Sound originates in Molar Vibrations.* — Fix a point on a stand so as to be nearly in contact with a glass bell (Figure 120), and also hang a pith ball in contact

Fig. 120.



with the bell on the opposite side. If we draw a rosined bow across the edge of the bell, this will be made to emit a musical sound, and will also be heard to tap against the point, showing that it is in vibration. The pith ball will also be kept swinging as long as the sound continues. On touching the bell lightly, we feel that it is vibrating.

By grasping it firmly, we stop both the vibration and the sound.

Strike one prong of a tuning-fork, and hold it to the ear; it is found to be emitting sound. Fill a glass brimful of water, and hold the edge of the prongs in contact with the water; a shower of spray will fly off on each side, showing that the prong is in vibration.

When a string or wire is emitting a sound, it may often be seen to be vibrating. It assumes the form of an elongated spindle (Figure 121).

Fig. 121.

Fig. 122.

If the front of an organ pipe is made of glass, and a little stretched membrane covered with sand is lowered into it (Figure 122), when the pipe is emitting a sound, the sand will be seen to be agitated, showing that the air within the pipe is in a state of vibration.

By similar experiments it has been ascertained that every body which is emitting sound is in a state of molar vibration. When the vibration stops, the sound ceases. The more intense the vibration, the louder the sound. Sound, therefore, originates in molar vibration of ordinary matter, solid, liquid, or gaseous.

161. *Fundamental and Harmonic Vibrations.* — Strew sand upon a horizontal plate of brass, and then, holding it with the thumb and finger (Figure 123), draw a bow across the edge of the plate so as to throw it into vibration. The sand will be tossed up and down at first, but will quickly come to rest in definite lines, called *nodal*

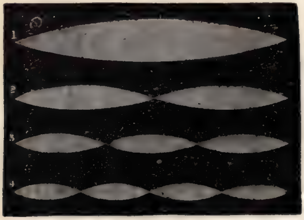
lines. These are lines of rest which separate the vibrating segments of the plate. By touching the plates at dif-

Fig. 123.

ferent points with the thumb and fingers, a great variety of figures may be produced with the sand, showing that it is possible for the plate to break up into vibrating segments in a great many different ways. A series of these nodal figures is shown in Figure 125.

Strings and columns of air may be also made to vibrate in segments. Figure 124 shows a string vibrating as a

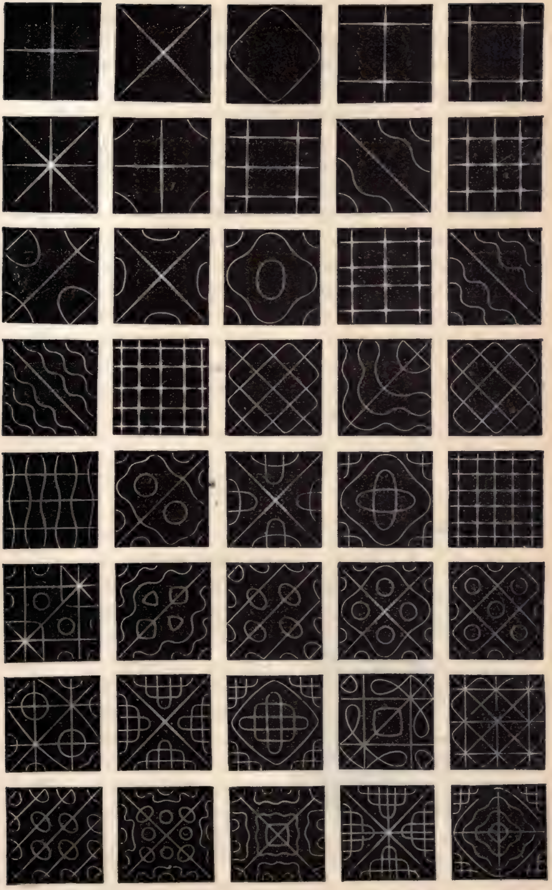
Fig. 124.



whole, in two segments, in three segments, and in four segments.

The vibration of a body as a whole is called its *funda-*

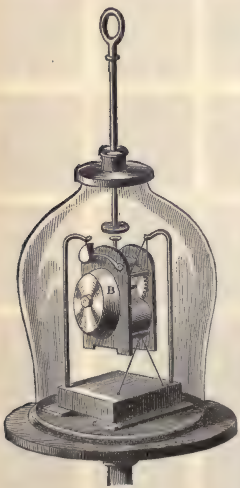
Fig. 125.



mental vibration; and the vibration of its segments, its *harmonic* vibration. The harmonic vibrations are more rapid than the fundamental vibrations. In a complete series of harmonic vibrations, the rate of vibration in the first harmonic is twice the fundamental rate; in the second harmonic, three times the fundamental rate; in the third harmonic, four times the fundamental rate; and so on. Usually some of the members of the series of harmonic vibrations are wanting in the case of vibrating bodies.

It is not only possible to produce harmonic vibrations in a body, but it is almost impossible not to produce them when a body is thrown into vibration. Whenever the fundamental vibration of a body is started, some of the harmonic vibrations are almost certain to be started with it. Hence it follows that the molar vibrations of bodies which originate sound are more or less complicated.

Fig. 126.



B. Propagation of Sound.

162. *Sound is not propagated in a Vacuum.* — In Figure 126 the bell B is suspended by silk threads under the receiver of the air-pump. The bell is struck by means of clock-work, which can be set in motion by the sliding-rod r. If the bell is struck before exhausting the air, it can be distinctly heard; but as the air is exhausted, the sound becomes fainter and fainter, until at last it can hardly be

perceived, even with the ear close to the receiver. Sound, then, cannot pass through a vacuum.

The slight sound which is heard is transmitted by the little air left in the receiver, and by the cords which hold up the bell.

163. *Sound is propagated in Gases, Liquids, and Solids.* — If hydrogen or any other gas is now allowed to pass into the receiver, the sound of the bell is heard again. If a bell is put under water and struck, it can be heard. If a person puts his ear close to the rail of an iron fence, and the rail is struck at a considerable distance, he hears the blow twice. The first sound comes through the rail; the second, which soon follows, comes through the air. These experiments show that sound passes through gases, liquids, and solids. Sounds are propagated chiefly by the air.

164. *Sound is propagated by Waves.* — When any vibrating body, as the prong of a tuning-fork, is moving forward, it crowds together the molecules of the air in front of it, and so produces a strain of compression in the air. As the body moves back again to its original position and beyond it on the other side, it allows the molecules of the air behind it to separate somewhat, and so produces a strain of rarefaction in the air. Each of these strains is propagated through the air from molecule to molecule in precisely the same way that the strain of compression was propagated from ball to ball in Figure 8. The molecules of air in front of the vibrating body simply vibrate to and fro with the sounding body. This vibrating motion is also propagated from molecule to molecule through the air; but while the strains of compression and rarefaction are continually moving forward, each molecule of air moves forward a short distance and then returns.

The strains of compression and rarefaction constitute what is called a *sound-wave*, and each strain is called a *phase* of the wave. If the body continues in vibration,

the phases of the waves will follow each other in regular succession.

The distance occupied by the two strains or phases is called the *length* of the wave. As the strain of compression is formed while the vibrating surface is moving forward, and the strain of rarefaction while the surface is moving backward, the length of each of these phases will be the distance the strain propagates itself while the sounding body performs half a vibration, and the length of the sound-wave will be the distance the strain can propagate itself while the sounding body is making a complete vibration. Hence, the faster the sounding body vibrates the shorter the sound-waves, and the slower it vibrates the longer the waves.

Fig. 127.

Since the sound-wave travels at the same rate in all directions in an open space, the outer surface of an advancing sound-wave is spherical. Figure 127 is a section

of a series of sound-waves advancing from a point at the centre of the section.

165. *The Intensity of Sound.* — The intensity of sound at any point depends upon the energy of the vibration of the molecules at that point.

As the sound-waves spread in all directions from the sounding body, a greater and greater number of particles of air must be set in motion, and the motion of each must be more feeble; and since the surfaces of spheres increase as the squares of their radii, the number of particles to be set in motion increases as the square of the distance from the sounding body. Sound, then, diminishes in intensity as the square of the distance from the sounding body increases.

If the sound-waves are prevented from spreading in all directions, the particles of air lose little of their motion, and the sound little of its intensity. Thus, Biot found that through one of the water-pipes of Paris words spoken in a very low tone could be heard at the distance of about three quarters of a mile. The sides of the pipe kept the sound-waves from spreading. In the same way conversation can be carried on between distant parts of a large building by means of small tubes, called *speaking-tubes.*

166. *The Velocity of Sound.* — The velocity of sound in air has been several times determined by experiment. In 1822 the French Board of Longitude chose two heights near Paris, and from the top of each fired a cannon at intervals of ten minutes during the night. The time between seeing the flash and hearing the report was carefully noted at both stations, and the average of the results showed that sound travels through the air at the rate of 1090 feet a second. In such experiments the time taken by the light to pass between the stations is too small to be perceived.

The velocity of sound in air depends somewhat upon the state of the atmosphere. Sound-waves travel faster with the wind than against it, and the higher the temperature of

the air, the greater the velocity of sound in it. The velocity given above is for the temperature of 32°.

The velocity of sound in water is about 4700 feet a second, and its velocity in solids is still greater.

167. *The Reflection of Sound.* — When sound-waves meet the surface of a new medium, they are, in part, thrown back, or *reflected.* In this reflection, as in all cases of reflected motion, the angles of incidence and reflection are equal to each other.

Echoes are produced by the reflection of sound. In order to get an echo, we must have a reflecting surface far enough away to give an appreciable interval between the direct and reflected sounds. When the surface is less than 100 feet distant, the reflected sound blends with the direct sound.

The reflecting surface has often such a shape as to cause the different portions of the reflected wave to converge to a point, and so to intensify the reflected sound.

Multiple echoes may be produced by successive reflections from surfaces at different distances on the same side, or by alternate reflections from two surfaces on opposite sides. In some localities a pistol-shot is repeated thirty or forty times.

Sound-waves are partially reflected on meeting a layer of air of a different density from that which they are traversing. Such layers of air often exist side by side in the atmosphere. This is one reason why the same sound will sometimes penetrate the atmosphere to a much greater distance than at others. The atmosphere is at such times free from these reflecting strata, which tend to stop the sound.

168. *The Refraction of Sound.* — When a portion of a sound-wave enters obliquely a new medium in which it travels at a different rate from that in the old, it experiences a change of front which alters the direction of the sound. This change of direction of sound on entering a new medium is called *refraction.*

Let *a b* (Figure 128) represent a portion of a sound-wave moving in the direction of the arrow, and *a c* be the surface of a medium *O*, of different density from *M*, in which the wave has been moving. If the elasticity of *O* is such that the wave will

move faster in it than in *M*, the portion *a* of the wave which enters *O* first will move on faster than the portion *b*, while the latter is moving in *M*. When *a b* is wholly within *O*, the second arrow shows the direction in which it will be moving; and it will continue to move in this direction so long as it is wholly in this medium. In this case the sound-wave is bent away from a perpendicular *P Q* drawn to the surface of the medium *O*.

If the elasticity of *O* is such that the sound-wave moves slower in it than in *M*, the portion *a* of the wave (Figure 129), when it has entered *O*, moves slower than *b*, while the latter is in *M*. In this case it will be seen that the direction of the wave will be bent towards the perpendicular *P Q*.

Fig. 128.

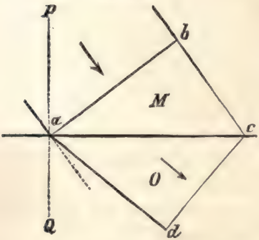
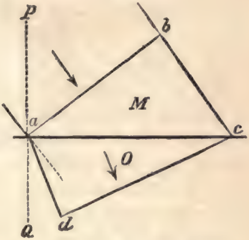


Fig. 129.



It is evident that if *a b* had not met the medium *O* obliquely, both ends of it would have entered *O* at the same time, and its direction would not have been changed.

We see, then, that when a sound-wave passes obliquely into a medium of different density, it is refracted, and that, if it travels more rapidly in the new medium, it will be bent away from a perpendicular drawn to the surface of that medium; while, if it travels less rapidly in the new medium, it will be bent towards a perpendicular drawn to the surface of that medium.

By refraction in passing from one layer of air to another, sounds may be made to pass over the head of an observer without being heard by him at all. This is probably one reason why sounds which are ordinarily audible in certain localities are

at other times not heard at all. At other times, especially in hilly regions, sounds which are ordinarily inaudible, because they pass overhead, may have their direction so changed by refraction or reflection as to reach the ear.

169. *Speaking and Ear Trumpets.* — The *speaking-trumpet* (Figure 130) consists of a long tube (sometimes

Fig. 130.

six feet long), slightly tapering towards the speaker, furnished at this end with a hollow mouth-piece, which nearly fits the lips, and at the other with a funnel-shaped enlargement, called the *bell*, opening out to a width of about a foot. It is much used at sea, and is found very effectual in making the voice heard at a distance. The explanation usually given of its action is, that the slightly conical form of the long tube produces a series of reflections in directions more and more nearly parallel to the axis; but this explanation fails to account for the utility of the *bell*, which experience has shown to be considerable.

The *ear-trumpet* is used by persons who are hard of hearing. It is essentially an inverted speaking-trumpet, and consists of a conical metallic tube, one of whose extremities, terminating in a *bell*, receives the sound, while the other end is introduced into the ear. This instrument is the reverse of the speaking-trumpet. The bell serves as a mouth-piece; that is, it receives the sound coming from the mouth of the person who speaks. These sounds are transmitted by a series of reflections to the interior of the trumpet, so that the waves, which would become greatly developed, are concentrated on the auditory apparatus, and produce a far greater effect than divergent waves would have done.

170. *The Form of Sound-Waves.* —The phases of compression and rarefaction in a sound-wave correspond to the elevation and depression of a water-wave. In the case of water-waves the molecules are vibrating up and down across the direction in which the wave is moving, that is to say, *transversely*. In the case of sound-waves the molecules are vibrating to and fro in the direction in which the wave is moving, or *longitudinally*. In water-waves the molecules vibrate up and down in paths which are nearly circles.

Imagine the waves of water pressed flat without any lateral spreading of the molecules. Where the waves were highest, the molecules of the flattened waves would be crowded closest together, and where the waves were lowest the molecules would be farthest apart. The elevation and depression of the waves would be converted into phases of compression and rarefaction. Moreover, the vertical circles in which the molecules of water are moving would be flattened into straight lines, and the molecules would vibrate longitudinally. By such flattening a

Fig. 131.

water-wave would be converted into a sound-wave, and the original form of the water-wave would be represented by certain states of compression in the different phases of the new wave.

By a reverse transformation, the state of compression and rarefaction in a sound-wave may be represented by a form similar to that of the water-wave.

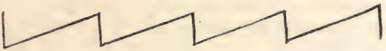
If we represent the state of compression or rarefaction of a sound-wave by a curve, the height of which at each point represents the degree of compression or rarefaction at that point, the curve will be highest where the condensation is greatest, and lowest where the rarefaction is greatest. Such a curve would have a form similar to that of a water-wave.

By the form of a sound-wave, we mean the state of rarefaction and compression in its phases, or rather, the form of the curve which would represent this state of rarefaction and compression. Figure 131 shows the form of the sound-wave that

would be produced by the fundamental vibration of a tuning-fork. This curve represents a *simple* wave-form. The molecules in this wave have a simple pendulous vibration.

When the fundamental and harmonic vibrations coexist in a body, as in a vibrating string, the motion of each point of the body is the resultant of the motions which each kind of vibration alone would give it. This is usually very far from a simple pendulous vibration. Figure 132 shows the form of the sound-wave produced by the vibration of the violin string. This is a *compound* wave-form. The vibration of the molecules in this wave-form is also compound; that is, it is the resultant of the combination of two or more kinds of vibration.

Fig. 132.



171. *Pitch of Sound.* — The *loudness*, or intensity, of sound depends upon the energy of the molecular vibrations in the sound-waves. In the curve representing the form of the sound-wave, the loudness would be represented by the height of the curves, or the *amplitude* of the wave.

The *pitch* of sound depends upon the rate at which the pulsations of sound strike upon the drum of the ear, or upon the length of the sound-waves. The length of the sound-waves depends chiefly upon the *rate of vibration* of the sonorous body.

Two sounds are said to be in *unison* when the rate of vibration is the same; to form an *octave*, when their rates of vibration are as 2 to 1; a *fifth*, when their rates of vibration are as 3 to 2; a *fourth*, when their rates of vibration are as 4 to 3; and a *major third*, when their rates of vibration are as 5 to 4.

In the lowest note of the organ there are 16½ vibrations a second. In the lowest note of the piano there are 33 vibrations a second, and in the highest note 4224; giving a range of 7 octaves. In the highest note ever heard in

an orchestra, there are 4752 vibrations a second. This note is given by the piccolo flute. In the shrillest sounds that are audible there are about 32,000 vibrations a second, the upper limit of audibility varying with different persons. The voice of ordinary chorus-singers ranges from 100 to 1000 vibrations a second, and the extreme limits of the human voice are 50 and 1500 vibrations a second.

172. *Quality of Sound.* — The *quality* of sound depends upon the form of the sound-waves, that is, upon the harmonic vibrations which are present with the fundamental vibration in the sonorous body. The pitch of sound is determined chiefly by the fundamental note. Two sounds of the same pitch may differ in quality, because of differences in their *harmonics*. *Fundamental* tones are those produced by the fundamental vibration of a sonorous body; and *harmonic* tones, those produced by the harmonic vibrations. No two instruments or voices give tones of the same quality, though they may be of the same loudness and pitch.

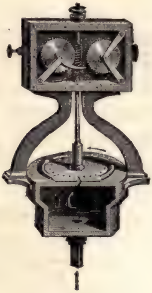
The difference between a *noise* and a *musical sound* is that the latter is smooth and regular, and the former rough and irregular. Musical sounds are produced by rapid *periodic* vibrations of a body, and noises by *non-periodic* vibrations.

173. *The Siren.* — The *siren* is an instrument used for ascertaining the rate of vibration in any note. It is shown in Figures 133 and 134, the former being a front, and the latter a back view. There is a small wind-chest, nearly cylindrical, having its top pierced with fifteen holes, at equal distances round the circumference of a circle. Just over this, and nearly touching it, is a movable circular plate, pierced with the same number of holes similarly arranged, and so mounted that it can rotate very freely about its centre, carrying with it the vertical axis to which it is attached. This rotation is effected by the action of the wind, which enters the wind-chest from below, and escapes through the holes. The form of the holes is shown by the sec-

tion in Figure 134. They do not pass perpendicularly through the plates, but slope contrary ways, so that the air when forced through the holes in the lower plate strikes against one side of the holes in the upper plate, and thus blows it around in a definite direction. The instrument is driven by means of the bellows. As the rotation of one plate upon the other causes the holes to be alternately opened and closed, the wind escapes in successive puffs, whose frequency depends upon the rate of rotation. Hence a note is emitted which rises in pitch as the rotation becomes more rapid. The siren will sound under water, if water

Fig. 133.

Fig. 134.



is forced through it instead of air; and it was from this circumstance that it derived its name.

In each revolution the fifteen holes in the upper plate come opposite to those in the lower fifteen times, and allow the compressed air in the wind-chest to escape, while in the intervening positions its escape is almost entirely prevented. Each revolution thus gives rise to fifteen vibrations; and in order to know the number of vibrations corresponding to the note emitted, it is only necessary to have a means of counting the revolutions.

This is furnished by a counter, which is represented in Figure 134. The revolving axis carries an endless screw, driving a wheel of 100 teeth, whose axis carries a hand traversing a dial marked with 100 divisions. Each revolution of the perforated

plate causes this hand to advance one division. A second toothed wheel is driven intermittently by the first, advancing suddenly one tooth whenever the hand belonging to the first wheel passes the zero of its scale. This second wheel also carries a hand traversing a second dial; and at each of the sudden movements just described this hand advances one division. Each division, accordingly, indicates 100 revolutions of the perforated plate, or 1500 vibrations. By pushing in one of the two buttons which are shown, one on each side of the box containing the toothed wheels, we can instantaneously connect or disconnect the endless screw and the first toothed wheel.

In order to determine the number of vibrations corresponding to any given sound which we have the power of maintaining steadily, we fix the siren on the bellows, the screw and wheel being disconnected, and drive the siren until the note which it emits is judged to be in unison with the given note. We then, either by regulating the pressure of the wind, or by employing the finger to press with more or less friction against the revolving axis, contrive to keep the note of the siren constant for a measured interval of time, which we observe by a watch. At the commencement of the interval we suddenly connect the screw and toothed wheel, and at its termination we suddenly disconnect them, having taken care to keep the siren in unison with the given sound during the interval.

The number of vibrations indicated on the dials for the interval (ascertained from the difference of readings at the beginning and end of it), divided by the number of seconds in the interval, will give the rate of vibration per second.

173. *The Composition of Waves.* — The following account of the composition of various systems of waves is from Helmholtz: —

"If a point of the surface of water is agitated by a stone thrown upon it, the agitation is propagated in rings of waves over the surface to more and more distant points. Now, throw two stones at the same time upon different points of the surface, thus producing two centres of agitation. Each will give rise to a separate ring of waves, and the two rings gradually expanding will finally meet. Where the waves thus come together, the water will be set in motion by both kinds of agitation at the same time;

but this in no wise prevents both series of waves from advancing further over the surface, just as if each were alone present and the other had no existence at all. As they proceed, those parts of both rings which had just coincided again appear separate and unaltered in form. These little waves, caused by throwing in stones, may be accompanied by other kinds of waves, such as those due to the wind or a passing steamboat. Our circles of waves will spread out over the water thus agitated, with the same quiet regularity as they did upon the calm surface. Neither will the greater waves be essentially disturbed by the less, nor the less by the greater, provided the waves never break ; if that happened, their regular course would of course be impeded.

"Indeed, it is seldom possible to survey a large surface of water from a high point of sight without perceiving a great multitude of different systems of waves, mutually overtopping and crossing each other. This is best seen on the surface of the sea, viewed from a lofty cliff, when there is a lull after a stiff breeze. We first see the great waves, advancing in far-stretching ranks from the blue distance, here and there more clearly marked out by their white foaming crests, and following one another at regular intervals towards the shore. From the shore they rebound, in different directions according to its sinuosities, and cut obliquely across the advancing waves. A passing steamboat forms its own wedge-shaped wake of waves, or a bird darting on a fish excites a small circular system. The eye of the spectator is easily able to pursue each one of these different trains of waves, great and small, wide and narrow, straight and curved, and observe how each passes over the surface, as undisturbedly as if the water over which it flits were not agitated at the same time by other motions and forces. I must own that whenever I attentively observe this spectacle, it awakens in me a peculiar kind of intellectual pleasure, because it bares to the bodily eye what the mind's eye grasps only by the help of a long series of complicated conclusions for the waves of the invisible atmospheric ocean.

"We have to imagine a perfectly similar spectacle proceeding in the interior of a ball-room, for instance. Here we have a number of musical instruments in action, speaking men and women, rustling garments, gliding feet, clinking glasses, and so on. All

these causes give rise to systems of waves, which dart through the mass of air in the room, are reflected from its walls, return, strike the opposite wall, are again reflected, and so on, till they die out. We have to imagine that from the mouths of men and from the deeper musical instruments there proceed waves of from 8 to 12 feet in length, from the lips of the women waves of 2 to 4 feet in length, from the rustling of the dresses a fine small crumple of waves, and so on; in short, a tumbled entanglement of the most different kinds of motion, complicated beyond conception.

"And yet, as the ear is able to distinguish all the separate constituent parts of this confused whole, we are forced to conclude that all these different systems of waves coexist in the mass of air, and leave one another mutually undisturbed. But how is it possible for them to coexist, since every individual train of waves has at any particular point in the mass of air its own particular degree of condensation and rarefaction, which determines the velocity of the particles of air to this side or that? It is evident that at each point in the mass of air, at each instant of time, there can be only one single degree of condensation, and that the particles of air can be moving with only one single kind of motion, having only one single amount of velocity, and passing in only one single direction.

"What happens under such circumstances is seen directly by the eye in the waves of water. If where the water shows large waves we throw a stone in, the waves thus caused will, so to speak, cut into the larger moving surface; and this surface will be partly raised and partly depressed by the new waves in such a way that the fresh crests of the rings will rise just as much above, and the troughs sink just as much below, the curved surfaces of the previous larger waves as they would have risen above or sunk below the horizontal surface of calm water. Hence, where a crest of the smaller system of rings of waves comes upon a crest of the greater system, the surface of the water is raised by the sum of the two heights; and where a trough of the former coincides with a trough of the latter, the surface is depressed by the sum of the two depths. This may be expressed more briefly if we consider the heights of the crests above the level of the surface at rest as positive magnitudes, and the

depths of the troughs as negative magnitudes, and then form the so-called algebraical sum of these positive and negative magnitudes, in which case, as is well known, two positive magnitudes (heights of crests) must be added, and similarly for two negative magnitudes (depths of troughs) ; but when both negative and positive concur, one is to be subtracted from the other. Performing the addition then in this algebraical sense, we can express our description of the surface of the water on which two systems of waves concur in the following simple manner: *The distance of the surface of the water at any point from its position of rest is at any moment equal to the sum of the distances at which it would have stood had each wave acted separately at the same place and at the same time.* Hence, although the surface of the water at any instant of time can assume only one single form, while each of two different systems of waves simultaneously attempts to impress its own shape upon it, we are able to suppose in the above sense that the two systems coexist and are superimposed, by considering the actual elevations and depressions of the surface to be suitably separated into two parts, each of which belongs to one of the systems alone.

"In the same sense, then, there is also a superimposition of different systems of sound in the air. By each train of waves of sound, the density of the air, and the velocity and position of the particles of air, are temporarily altered. There are places in the wave of sound comparable with the crests of the waves of water, in which the quantity of the air is increased, and the air, not having free space to escape, is condensed; and other places in the mass of air, comparable to the troughs of the waves of water, having a diminished quantity of air, and hence diminished density. It is true that two different degrees of density, produced by two different systems of waves, cannot coexist in the same place at the same time; nevertheless, the condensations and rarefactions of the air can be (algebraically) added, exactly as the elevations and depressions of the surface of the water in the former case. Where two condensations are added we obtain increased condensation, where two rarefactions are added we have increased rarefaction ; while, if a condensation and rarefaction concur, they mutually, in whole or in part, destroy or neutralize each other.

"The displacements of the particles of air are compounded in a similar manner. For the magnitude of these displacements as well as for the velocities with which the particles of air move outward and inward, the same (algebraical) addition holds good as for the crests and troughs of waves in water.

"Hence, *when several resonant bodies in the surrounding atmosphere simultaneously excite different systems of waves of sound, the changes of density of the air, and the displacements and velocities of the particles of the air within the passages of the ear, are each equal to the (algebraical) sum of the corresponding changes of density, displacements, and velocities which each system of waves would have separately produced, if it had acted independently;* and in this sense we can say that all the separate vibrations which separate waves of sound would have produced, coexist undisturbed at the same time within the passages of our ear."

174. *Interference of Sound.* — When two equal water-waves meet in the same phase, namely, so that the crest of one coincides with the crest of the other, and the hollow of one with the hollow of the other, their combination produces at the point of meeting a wave of double the height. Were the two waves to meet in opposite phases, that is, so that the hollow of one coincides with the crest of the other, their combination would leave the surface of the water undisturbed. There would be neither depression nor elevation.

In a similar way, when two equal sound-waves meet in the same phase, their combination would produce at the point of meeting a wave of twice the degree of condensation and rarefaction of either of the component waves. Were the two waves to meet in opposite phases, the air would be undisturbed at the place of meeting. There would be neither condensation nor rarefaction. An ear at the point of meeting of the waves in the first case would hear a sound much louder than that conveyed by either sound-wave

alone; while in the second case it would hear no sound at all. The meeting of two sound-waves so as to neutralize each other is called the *interference* of sound.

Strike a tuning-fork so as to throw its prongs into vibration, and hold it vertically near the ear, and turn it slowly around so as to bring the sides, the edges, and the corners of the prongs successively towards the ear. Four positions of the fork will be found in which its sound will be inaudible. Let *a* and *b* (Figure 135) be the ends of the prongs of a tuning-fork in vibration. The sound of the fork is inaudible when the ear is on any one of the dotted lines. As the prongs vibrate, each develops a series of waves, and along the dotted lines these two sets of waves will be of equal intensity and in opposite phases. Hence along these lines the two sets of waves neutralize each other, and silence results from the combination of two sounds.

Fig. 135.

175. *Musical Beats.* — Suppose two tuning-forks, slightly different in pitch, to be started together, and suppose the prongs of both to be moving forward at the same time; they will start waves of the same phase which will coincide with and intensify each other. The fork having the higher pitch will, however, immediately begin to gain on the other, and the coincidence of the waves will be less and less perfect until this fork has gained half a vibration on the other. The prongs of the two forks will now be moving in opposite directions at the same time, and the waves started by the two forks will be in opposition, and will neutralize each other wholly or in part. After this there will again be partial coincidence of the waves, and the degree of coincidence will increase till the higher fork has gained a whole vibration on the lower one, when the coin-

cidence will again be complete. When two such forks are started together, the sound gradually dies away till it becomes nearly or altogether inaudible; it then swells out loudly, and gradually dies away again at regular intervals. These gradual risings and fallings in the intensity of sound are called *beats*.

These beats occur whenever two sounds of nearly the same pitch are produced together. The rate of beating will be equal to the difference of the rate of vibration in the two sonorous bodies. If one of the bodies gains one vibration a second on the other, the sounds will beat once a second; if it gains two vibrations a second, the sounds will beat twice a second; and so on.

The less the sounds differ in pitch the slower the beats, and the more they differ in pitch the more rapid the beats.

Even after the beats become too rapid to be distinguished by the ear, they give a disagreeable roughness to the sound. According to Helmholtz, dissonance is entirely due to the roughness produced by a rapid succession of beats, which take place between either the fundamental tones or the harmonics which are present in the two sounds.

C. Resonance.

176. *Sympathetic Vibrations of Tuning-Forks.* — Take two tuning-forks of exactly the same pitch, cause one of them to vibrate, and hold it near the other without touching it. The second fork will soon begin to vibrate, and will emit a distinctly audible sound after the first has been stopped. The second fork will not be started by the first unless the two are of exactly the same pitch, as may be shown by sticking a little pellet of wax to the prong of one of the forks so as to diminish its rate of vibration. Vibrations started in one body by the vibrations of another are called *sympathetic* vibrations. The production of sound by sympathetic vibrations is called *resonance*.

The vibrations are communicated from one fork to the other by means of the air. The vibrations of the first fork produce condensations and rarefactions in the air which succeed each other at the rate at which the fork is vibrating. The number of condensations which would pass any point in the room in a second is exactly equal to the number of vibrations executed by the fork in a second. In the condensations the pressure of the air is increased, and in the rarefactions it is diminished. Each condensation as it passes the prong of the second fork gives it a little push. As the second fork vibrates at exactly the same rate as the first, each condensation arrives in time to push the prong just as it is ready to move forward of itself. Hence the prong is always pushed in the direction in which it is moving. The push of one condensation moves the prong but little, but the pushes are so timed that each moves it a little farther than the last, until the fork is made to vibrate strongly. The elasticity and inertia of the fork are such that it still continues to vibrate when it has been started, even though the first fork is stopped.

When the second fork cannot vibrate at the same rate as the first, the condensation will sometimes push in the direction in which the prong is moving and sometimes in the opposite direction. Hence one push will neutralize the effect of another instead of augmenting it.

177. *Sympathetic Vibrations of Strings.* — If a piano is opened and one of the keys gently depressed so as to raise the damper without striking the string with the hammer, and the note of the string is then sung over the piano, the string will begin to vibrate and will emit an audible sound for a little time after the voice ceases. It is only necessary to hit the pitch of a string accurately and to sustain the note sufficiently. Sympathetic vibrations are started more readily in strings than in tuning-forks, but they are less persistent. They very soon die away after the excit-

ing sound ceases. Strings may be thrown into vibration by their harmonic notes as well as by their fundamental notes.

178. *Sympathetic Vibrations of Thin Membranes.* — Thin membranes when stretched are very readily thrown into sympathetic vibration, but their vibrations stop promptly when the exciting sound ceases. Owing to the facility with which they break up into vibrating segments, they respond readily to all rates of vibration. The same is true of thin metallic plates.

179. *Sympathetic Vibrations of Masses of Air.* — If a vibrating tuning-fork is held at the end of a tube an inch and a half or two inches in diameter, the sound of the fork will be powerfully reinforced, provided the tube is of suitable length. The suitable length for a tube open at both ends is one half of the length of the wave produced by the fork. A tube closed at one end resounds most powerfully when its length is one quarter of the length of the wave produced by the fork. The column of air in the tube is thrown into powerful sympathetic vibration by the fork, and these vibrations greatly augment the sound. The moment the fork is stopped the resonance ceases.

Columns of air may also be thrown into sympathetic vibration by their harmonic vibrations. By altering the shape of the tube it may be made to reinforce certain harmonics more powerfully than others, and so change the quality of the exciting sound.

180. *Sounding Boards and Boxes.* — The sound of a tuning-fork is feeble unless reinforced by a resonant case of suitable dimensions to which the fork is fixed. Such a resonant case is called a *sounding-box.*

Thin pieces of dry straight-grained pine, such as are employed for the faces of violins and the sounding-boards of pianos, are capable of vibrating more or less freely, in any period lying between certain wide limits. They are

accordingly set in vibration by all the notes of their re spective instruments; and by the large surface with which they act upon the air, they contribute in a very high degree to increase the sonorous effect. All stringed instruments are provided with sounding-boards; and their quality mainly depends on the greater or less readiness with which these respond to the vibrations of the strings.

D. Musical Instruments.

181. *Stringed Instruments.* — In one class of musical instruments the notes are produced by the transverse vibrations of strings. These instruments are called *stringed* instruments. The rate at which a string vibrates depends upon its length, its weight, and its tension. The *shorter*, the *tighter*, and the *lighter* a string, the faster it vibrates. Strings may be thrown into transverse vibration by drawing a rosined bow across them, as in the case of the violin; or by plucking them with the finger, as in the case of the harp; or by striking them with a hammer, as in the case of the piano.

In the piano there is a string for every note. In the violin and similar instruments, several notes are obtained from the same string by fingering it so as to change its length and tension.

Fig. 136.

182. *The Sonometer.* — The *sonometer* is an instrument for investigating the laws of the vibration of strings. It is shown in Figure 136. It consists essentially of a string

or wire stretched over a sounding-box by means of a weight. One end of the string is secured to a fixed point at one end of the sounding-box; the other end passes over a pulley, and carries weights which can be altered at pleasure. Near the two ends of the box are two fixed bridges, over which the cord passes. There is also a movable bridge, which can be employed for altering the length of the vibrating portion.

183. *Wind Instruments.* — In *wind* instruments the notes are produced by the longitudinal vibrations of columns of air enclosed in pipes. The rate of vibration depends upon the length of the column, and upon whether the pipe is open or is closed. The shorter a column of air the faster it vibrates, and the air in an open tube vibrates twice as fast as that in a closed pipe of the same length. This is because the air in a closed pipe vibrates as a whole, while that in an open pipe vibrates in two segments, there being a stationary point or *node* at the centre of the pipe. In an organ there are as many pipes as notes, only one note being obtained from each pipe. In the case of the flute and similar wind instruments, several notes are obtained from one pipe by opening and closing the holes at the side of the pipe so as to alter the length of the vibrating column of air, and by altering the strength of the blast so as to change from the fundamental note of the pipe to one or other of its harmonics.

In all wind instruments the pipe is made to speak by resonance. The sympathetic vibrations in the pipe are sometimes started by the vibrations of the lips, as in the case of the trumpet; or by the vibrations of a spring called a *reed*, as in the case of the clarionet; or by the flutter of a jet of air when blown against a sharp edge, as in the case of the flute.

184. *Organ Pipes.* — Organ pipes are made of wood or metal, and they are made to speak either by blowing

against a sharp edge so as to produce a flutter, or by blowing against a spring so as to throw it into vibration. Pipes which are made to speak in the first way are called *flue-pipes*; and those made to speak in the second way, *reed-pipes*. Pipes closed at one end are called *stopped* pipes; and those open at both ends, *open* pipes.

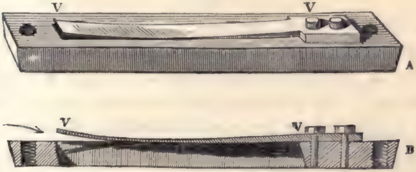
Fig. 137.

Fig. 138.

These pipes are shown in Figures 137 and 138. The air passes from the bellows through the tube P into a chamber, which is closed at the top except the narrow slit i. The air compressed in the chamber passes through this slit in a thin sheet, which breaks against a sharp edge a, and there produces a flutter. The space between the edge a and the slit below is called the *mouth* of the pipe.

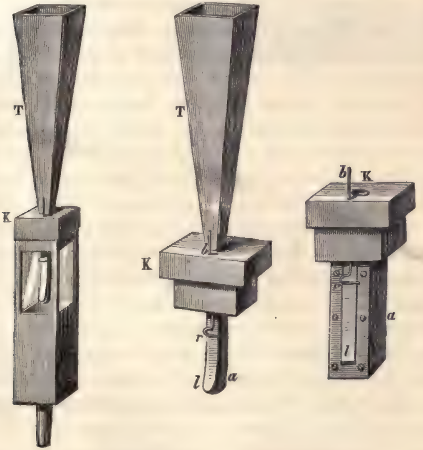
The metal reed commonly used in organ pipes is shown in Figure 139. It consists of a long strip of flexible metal

Fig. 139.



V V, placed in a rectangular opening, through which the current of air enters the pipe. As soon as the air begins

Fig. 140.



to enter the pipe, the force of the blast bends down the spring of the reed so as to close the opening. The elas-

ticity of the reed causes it to fly back at once, so as to open the pipe and allow the air to enter again. It thus breaks up the current of air into a regular succession of little puffs.

The way in which the reed and pipe are connected is shown in Figure 140. The reed is placed within the chamber *K*, into which air is forced through the tube at the bottom. *T* is a conical pipe of metal, the opening of which is covered by the reed as already explained. The wire *b r* is used to lengthen or shorten the reed, and thus to vary its rate of vibration.

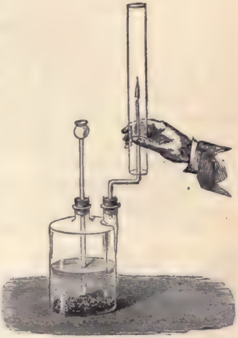
The *quality* of the sound of an organ pipe depends chiefly upon the shape of the pipe, which causes it to reinforce more or less powerfully certain of the harmonics which are present with the fundamental note.

185. *The Organ of the Human Voice.* — The organ of voice in man is situated at the top of the windpipe, or *trachea*, which is the tube through which the air is blown from the lungs. A pair of elastic bands, called the *vocal chords*, stretched across the top of the windpipe so as nearly to close it, form a double reed. When the air is forced from the lungs through the slit between the chords, these are made to vibrate. By changes in their tension, their rate of vibration is varied, and the sound raised or lowered in pitch. The cavity of the mouth and nose acts as a resonant tube, and by altering the shape of this cavity we can give greater prominence either to the fundamental note of the vocal chords or to any of their harmonics.

186. *Singing Flames.* — The air in an open tube may be made to give a sound by means of a luminous jet of hydrogen, coal gas, etc. When a glass tube about twelve inches long is held over a lighted jet of hydrogen (Figure 141), a note is produced, which, if the tube is in a certain position, is the fundamental note of the tube. The current of air passing up through the tube over the flame causes

the flame to flutter, and the air in the tube reinforces some pulsations of this flutter by sympathetic vibration. The vibration of the column of air in the tube reacts upon the flame, and causes it to vibrate more regularly and more powerfully. The note depends on the size of the flame and the length of the tube; with a long tube, by varying the position of the jet in the tube, a series of notes in the ratio 1 : 2 : 3 : 4 : 5 is obtained.

Fig. 141.



If, while the tube emits a certain sound, the voice or the siren is gradually raised to the same pitch, as soon as the note is nearly in unison with that of the tube, the flame becomes agitated, jumps up and down, and is finally steady when the two sounds are in unison. If the note of the siren is then gradually raised, the pulsations again commence; they are the optical expressions of the beats which occur near perfect unison. If, while the jet burns in the tube and produces a note, the position of the tube is slightly altered, a point is reached at which no sound is heard. If now the voice, or the siren, or the tuning-fork is pitched at the note produced by the jet, it begins to sing, and continues to sing even after the siren is silent. A mere noise or shouting at an incorrect pitch affects the flame, but does not cause it to sing.

E. Analysis of Sound.

187. *Analysis of Sound by Resonance.* — We have seen that sound originates in molar vibrations, and that it is propagated

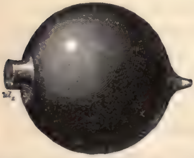
by waves chiefly through the air. Very few sounds are simple, most sounds being composed of various mixtures of fundamental and harmonic tones. Most sound-waves are compound. Sound-waves are compounded like water-waves, but there is one essential difference between the two cases. A compound water-wave has but a momentary existence; the long waves move over the surface of water faster than the short ones. Hence, when two sets of water-waves of different lengths unite, they quickly separate again, and enter into new combinations. When two sets of sound-waves moving in the same direction combine, the combination is permanent, since long and short waves traverse the air at the same rate.

These compound wave-forms may be decomposed into their constituent elements by means of resonance.

188. *The Analysis of Sound by the Resonance of Strings.* — If we raise the dampers of a piano, and sing any one of the vowels, *A*, *E*, *O*, and *U*, strongly over the piano, the strings which are capable of vibrating at the rate of any of the tones in the vowel sounds will be thrown into sympathetic vibration. When one stops singing over the piano, the strings will, by their resonance, give back the vowel sound. The different strings which were thrown into sympathetic vibration produce by their joint vibrations a compound wave of the same form as that which left the mouth when it uttered the vowel. This compound wave is first decomposed by the strings into its constituent elements, and then these elements are again recombined in the new wave formed by the vibrating strings.

189. *The Analysis of Sound by Means of Resonators.* — Helmholtz devised an instrument for the analysis of sound which he called a *resonator*. One of these resonators is shown in Figure 142. It is a hollow globe of thin brass, with an opening at each end. The larger opening is for the admission of sound, and the smaller one for insertion into the ear. The enclosed mass of air has, like the column of air in an organ pipe, a particular fundamental note of its own, depending upon its size; and whenever a note of this

Fig. 142.



particular pitch is sounded in its neighborhood, the enclosed air takes it up and intensifies it by resonance. In order to test the presence or absence of a particular harmonic in any sound, a resonator in unison with the harmonic is applied to the ear. If the resonator speaks, the harmonic is present. These instruments are usually constructed so as to form a series whose notes correspond to the bass *C* of a man's voice and its successive harmonics as far as the tenth or twelfth.

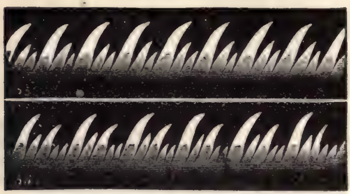
190. *Koenig's Manometric Flames.* — The vibrations of air may be transferred to gas-flames, and thus rendered visible. The gas is first conducted through a tube to a little gas-chamber, one side of which is formed of a very thin sheet of india-rubber. The tube at the end of which the gas is burned issues from one side of this chamber. One form of the chamber is shown in Figure 143. The vertical line at the centre of the section represents the stretched membrane of india-rubber. The gas is admitted into the little chamber to the right of this membrane through the tube fitted with the stopcock, and escapes through the tube above, at the end of which it is burned. The part to the left of the membrane is for the purpose of connecting the chamber to a mouth-piece or any other apparatus by means of a rubber tube. The vibrations of the air being taken up by the membrane, and thus communicated to the gas, cause the flame to leap up and down. These oscillations of the flame are so rapid and regular that, when viewed directly, the flame appears to be quite steady. Its altered condition, however, betrays itself by an altered form and color. But to see the separate oscillations, the flames should be viewed in a rotating mirror, in which the flame at rest appears to be drawn out into a long uniform ribbon, while the oscillating flame appears as a series of separate images of flames. Figure 144 shows a small mirror, mounted so that it

Fig. 143.

Fig. 144.

may be rotated on a vertical axis by the thumb and fingers, and also shows the appearance of the vibrating flame as reflected in the rotating mirror. Every change of pressure upon the stretched membrane will be represented by a different height of the reflected flame. Figures 145 and 146 show the appear-

Figs. 145, 146.



ance of the flame in the mirror on singing the vowel sound *a* into the mouth-piece on the notes *F* and *C*.

191. *Edison's Phonograph.* — In Edison's *phonograph*, the vibrations of the air are first taken up by a thin plate of metal, and are then permanently registered on a sheet of tin-foil. This instrument is shown in Figure 147. It consists essentially of a brass cylinder *C* and of a mouth-piece *F*. On the surface of the cylinder is constructed a very accurate spiral groove, the

Fig. 147.

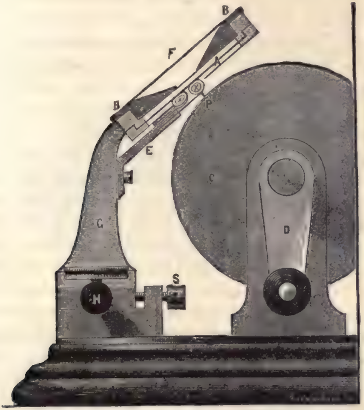
threads of which are about $\frac{1}{10}$ of an inch apart. The cylinder is turned by the crank *D* upon the axis *A B*. On one end of this axis is cut a thread of the same fineness as the groove on the cylinder. A sheet of tin-foil is fastened smoothly on the surface of the cylinder.

An enlarged view of the mouth-piece is shown in Figure 148.

This mouth-piece is supported on a post G, and may be moved to and from the cylinder by the lever H. At the bottom of the mouth-piece there is an iron plate A about $\frac{1}{100}$ of an inch thick. Under this plate are two pieces of rubber tubing x and x, which separate it from a spring supported by E, and carrying a round steel point P.

The point P rests upon the tin-foil on the cylinder, just over the spiral groove. If the crank is turned, the thread on the axis causes the cylinder to move forward so as to keep the groove always under the point. When the iron plate is at rest, if we

Fig. 148.



turn the crank the point marks a spiral line of uniform depth on the tin-foil. If we speak or sing into the mouth-piece, the vibrations of the air are communicated to the iron plate, and from this to the point by means of the rubber tube. If the crank is turned while speaking or singing into the mouth-piece, the point will mark a dotted line on the tin-foil. The depth of the indentations made by the point in the tin-foil will exactly represent the densities of the different portions of the sound-waves which encounter the disc. The forms of the sound-waves are thus

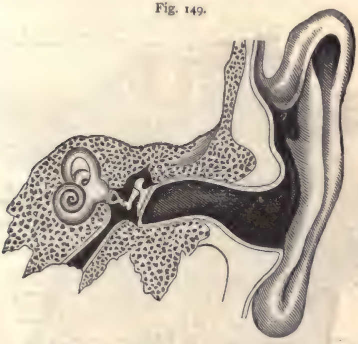
registered on the tin-foil, and may be studied at leisure with the microscope.

If, after talking into the mouth-piece, the cylinder is again set back to the starting-point and the crank is then turned, the point will follow the indentations in the tin-foil, and so be compelled to vibrate exactly as it did when it made these indentations in the foil. The vibrations of the point will be communicated to the thin iron plate by means of the rubber tube, and by the plate to the air. Thus the words spoken into the mouth-piece will be exactly repeated, and by the use of a properly constructed mouth-piece they are rendered audible throughout a large hall. By resetting the cylinder, they may be repeated several times, though more feebly each time the foil is passed under the point; the indentations of the foil being gradually smoothed out.

192. *The Analysis of Sound by the Human Ear.* — A section of the human ear is shown in Figure 149. In this organ we have, first of all, the external opening of the ear, which is closed at the bottom by a circular membrane called the *tympanum*. Behind this is the cavity called the *drum* of the ear. This cavity is separated from the space between it and the brain by a bony partition, in which there are two openings, the one round and the other oval. These also are closed by delicate membranes. Across the cavity of the drum stretches a series of four little bones : the first, called the *hammer*, is attached to the tympanum ; the second, called the *anvil*, is connected by a joint with the hammer ; a third little round bone connects the anvil with the *stirrup* bone, which has its oval base planted against the membrane of the oval opening, almost covering it. Behind the bony partition, and between it and the brain, we have the extraordinary organ called the *labyrinth*, which is filled with water, and over the lining of which the fibres of the auditory nerve are distributed. The tympanum intercepts the vibrations of the air in the external ear, and transmits them through the series of bones in the drum to the membrane which separates the drum from the labyrinth ; and thence to the liquid within the labyrinth itself, which in turn transmits them to the nerves. The transmission, however, is not direct. At a certain place within the labyrinth, exceedingly fine elastic bristles, terminating in sharp points, grow up between the nerve fibres. These bristles, dis-

covered by Max Schultze, are exactly fitted to sympathize with those vibrations of the water which correspond to their proper periods. Thrown thus into vibration, the bristles stir the nerve fibres which lie between their roots, and the nerve transmits the impression to the brain, and thus to the mind. At another place in the labyrinth we have little crystalline particles, called *otoliths*, — the *Hörsteine* of the Germans, — embedded among the nervous filaments, and exerting, when they vibrate, an intermittent pressure upon the adjacent nerve fibres. The otoliths probably answer a different purpose from that of the bristles of Schultze.

Fig. 149.

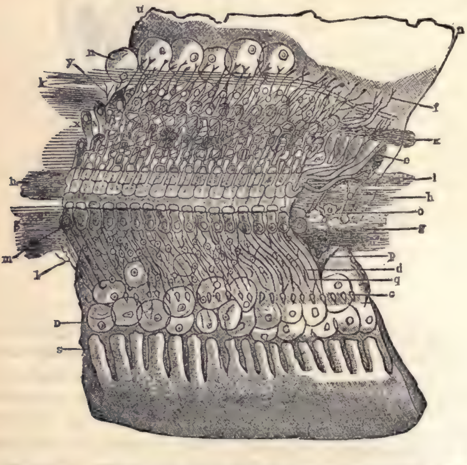


They are fitted, by their weight, to receive and prolong the vibrations of evanescent sounds which might otherwise escape attention. The bristles of Schultze, on the contrary, because of their extreme lightness, would instantly yield up an evanescent motion, while they are peculiarly fitted for the transmission of continuous vibrations. Finally, there is in the labyrinth a wonderful organ, discovered by Corti, which is to all appearance a musical instrument, with its chords so stretched as to receive vibrations of different periods, and transmit them to the nerve filaments which traverse the organ. Within the ear of man, and without his knowledge or contrivance, this lute of 3000 strings has existed for ages, receiving the music of the outer world, and rendering it fit for reception by the brain.

Each musical tremor which falls upon this organ selects from its tense fibres the one appropriate to its own pitch, and throws that fibre into sympathetic vibration. And thus, no matter how complicated the motion of the external air may be, these microscopic strings can analyze it, and reveal the elements of which it is composed.

Figure 150 is an enlarged view of a portion of Corti's organ. Helmholtz says of this organ: "The arches which leave the membrane at *d* and are reinserted at *e*, reaching their greatest height between *m* and *o*, are probably the parts which are suited

Fig. 150.



for vibration. They are spun round with innumerable fibrils, among which some nerve fibres can be recognized, coming to them through the holes near *c*. The transverse fibres *g*, *h*, *i*, *k*, and the cells *o*, also appear to belong to the nervous system. There are about three thousand arches similar to *d*, *e*, lying orderly beside each other, like the keys of a piano, in the whole length of the partition of the cochlea."

III.

HEAT.

I.

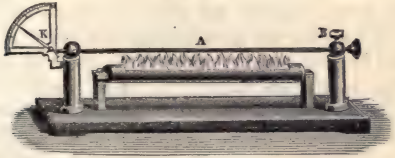
EFFECTS OF HEAT.

A. Expansion.

193. *Expansion of Solids.* — As a rule, bodies expand when heated, solids being the least expansible, liquids next, and gases the most expansible.

In the case of solids which have a definite figure, we may consider the expansion in length, or *linear expansion*, only; or the expansion in length and breadth, or *superficial expansion;* or expansion in length, breadth, and thickness, or *cubical expansion.* Though we may consider these expansions apart, they in reality all occur together.

Fig. 151.

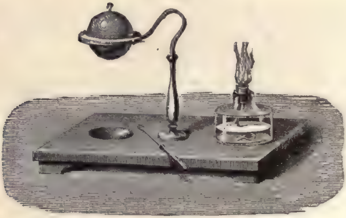


The linear expansion of a solid may be illustrated by means of the apparatus shown in Figure 151. The metal rod *A* is supported on two standards. It is fastened at the end *B* by the binding screw. The other end passes loosely through its standard, and presses against the short

arm of the index *K*, which moves over a graduated arc. Under the rod there is a vessel filled with alcohol. The rod is adjusted so that the index shall be at zero on the scale, and the alcohol is lighted. As the alcohol burns, the rod becomes heated, and the index rises. The rise of the index shows that the rod has expanded in length so as to move forward the short arm of the index.

If a brass and iron rod of the same length and thickness are tried in succession, and each is raised to a bright red heat, it will be found that the brass rod will expand considerably more than the iron. As a rule different solids expand unequally when heated equally.

Fig. 152.

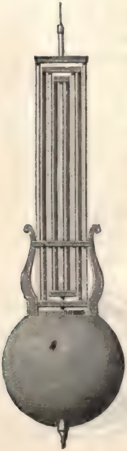


The cubical expansion of a solid may be illustrated by means of the ring and ball shown in Figure 152. When cool, the ball will just pass through the ring. If we heat the ball by holding it for a time in the flame of the lamp, it will no longer pass through the ring; but if allowed to cool, it will again pass through the ring. If, while the heated ball rests on the ring, the ring is heated equally with the ball, the latter will again pass through the ring, the two being equally expanded by the heat.

194. *Force of Expansion of Solids.* — The *force* of expansion is very great, being equal to that which would be necessary to compress the body to its original dimensions. Thus, for instance, iron when heated from 32° to 212°

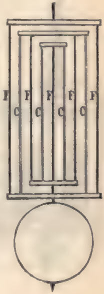
increases by .0012 of its original length. In order to produce a corresponding change of length in a rod an inch square, a force of about 15 tons would be required. It would be useless to attempt to offer any mechanical resistance to a force so enormous; the only thing that can be done, in the case of structures in which metals are employed, is to arrange the parts in such a manner that the expansion shall not be attended with any evil effects. Thus, in a railway, the rails do not touch each other, a small interval being left to allow room for the variations of length. Iron beams employed in buildings must have the ends free to move forward, without encountering any obstacles, which they would inevitably overthrow. Sheets of zinc and lead employed in roofing are so arranged as to be able to overlap one another on expansion.

Fig. 153.



195. *Compensating Pendulum.* — The pendulum, as we know, regulates the motion of a clock. Suppose the clock to keep exact time at the temperature of the freezing-point; then, if the temperature rises, the length of the pendulum will increase, and with it the duration of each oscillation, so that the clock will lose. The opposite effect would be produced by a fall of the temperature below the freezing-point. We thus see that clocks are liable to go too fast in winter, and too slow in summer, and that we must move the ball of the pendulum from time to time in order to insure their regularity.

Fig. 154.



The effect of temperature may be notably diminished by means of *compensating pendulums*, of which there are several different kinds.

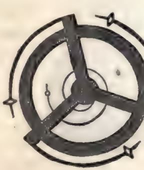
Harrison's gridiron pendulum (Figures 153 and 154) consists of four oblong frames, the uprights of which are alternately of brass, *C*, and of steel, *F*. The brass uprights rest upon the bottom cross-bars of the steel frames. The second pair of steel uprights are suspended from the cross-bar resting on the top of the first pair of brass uprights. The pendulum rod is hung from the top cross-bar of the second pair of brass uprights. It will be seen that the expansion of the steel rods alone would tend to lower the ball, while the expansion of the brass rods alone would tend to raise it. The lengths of the steel rods are, of course, greater than those of the brass rods; but as brass expands more rapidly than steel, the lengths of the rods may be so adjusted that the expansion of one set of rods shall just balance that of the other, so that the ball of the pendulum shall be kept all the time at exactly the same distance from the point of suspension.

Fig. 155.

Graham's pendulum consists of an iron rod carrying at the bottom a frame which holds one or two tubes containing mercury (Figure 155). The mercury takes the place of the ball of the pendulum. The expansion of the rod alone would tend to lower the centre of gravity of the mercury, while the expansion of the mercury alone, since the mercury is free to expand only upward, would tend to raise the centre of gravity. The quantity of mercury is adjusted so that its expansion shall balance that of the rod, and thus keep the centre of gravity of the mercury at the same height all the time.

196. *Compensation Balance-Wheel.* — The rate of a watch is controlled by the vibration of the *balance-wheel*. The larger this wheel, the slower it vibrates, and the smaller it is the faster it vibrates. Hence changes of temperature have the same

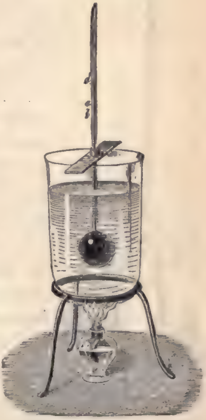
Fig. 156.



effect on the rate of watches as on that of clocks. The rim of the *compensation balance-wheel* is made in sections, which are supported by metallic rods, radiating from the centre of the wheel (Figure 156). The sections are weighted at their free ends, and are composed of two metals having different degrees of expansibility, the more expansible metal being on the outer side of the sections. The expansion of the rods alone would tend to carry the weights away from the centre of the wheel and so to make the wheel larger. When the sections of the rim expand, they become more curved, since they expand more rapidly on the outside than on the inside. Hence the expansions of the sections alone would tend to carry the weight in towards the centre and so to make the wheel smaller. The parts of the wheel may be so adjusted that the expansion of the sections of the rim shall just balance that of the supporting rods.

197. *Expansion of Liquids.* — The expansion of a liquid may be illustrated by means of a bulb with a projecting tube, as shown in Figure 157. The bulb and stems are filled with water or other liquid up to the point *a*. On immersing the bulb into a vessel of hot water, the liquid in the stem at first falls to *b*, and then gradually rises to *a*. The liquid falls at first, because the bulb, being the first heated, is also the first to expand, and as the capacity of the bulb increases, the liquid falls in the stem. Afterwards, as the liquid becomes heated, it also expands, and that more rapidly than the globe. Hence the rise of the liquid in the tube.

Fig. 157.



If two bulbs, with projecting tubes, and of exactly the same

size, are filled, one with water and the other with alcohol, and are then heated equally, the alcohol will be seen to expand more rapidly than the water. And in general, different liquids when heated equally expand unequally.

198. *Anomalous Expansion and Contraction of Water.* — If a bulb and tube are filled with water, and the bulb surrounded with a freezing mixture, the water in the stem will steadily fall till the temperature of the water has reached 39°; it will then begin to rise again, and will continue to rise till the temperature reaches 32°. If now the bulb is gradually heated, the water will fall in the stem till the temperature reaches 39°; it will then begin to expand, and will continue to expand until it boils. Water at 39° will expand whether it is heated or cooled. It follows from this, that water is at its greatest density at 39°. Hence this point of temperature is called its *point of maximum density.*

Fig. 158.

199. *Expansion of Gases.* — The expansion of air may be illustrated by means of the bulb and tube shown in Figure 158. The bulb is filled with air, which is separated from the external air by a small column of liquid in the stem, which serves also as an index. When the globe is warmed by the hands, the index is rapidly pushed up, showing that the air has expanded. It has been found that all gases expand equally for the same rise of temperature, and that under a uniform pressure a gas will expand so as to double its volume for a rise of temperature of about 490°.

200. *Expansion due to an Increase of Molecular Motion.* — The molecules of bodies are all the time moving rapidly to and fro. When heat is applied to a body,

its molecules are made to move more rapidly, and this increased agitation of the molecules causes them to move farther apart, and the body to expand.

B. Measurement of Temperature.

201. *Temperature.* — When we wish to indicate *how hot* a body is, we say that it has a certain *temperature.* The word *temperature* is the noun which corresponds to the adjective *hot.* We estimate how hot a body is from its power of imparting heat to other bodies. The body which has the greater power of imparting heat is said to be the hotter, or to have the higher temperature.

Temperature is the thermal condition of a body considered with reference to its power of imparting heat to other bodies.

An instrument used for measuring temperature is called a *thermometer.*

202. *Mercurial Thermometer.* — In ordinary thermometers changes of temperature are indicated and measured by the expansion and contraction of mercury. The instrument is called a *mercurial thermometer.* It consists essentially, as shown in Figure 159, of a tube with a very fine calibre, closed at one end, and having a reservoir at the other end, usually in the form of a globe or cylinder. The bulb and a portion of the stem are filled with mercury. As the temperature changes, the top of the column of mercury in the tube rises and falls. A scale is either engraved on the stem or placed behind it.

Fig. 159.

203. *Construction of the Mercurial Thermometer.* — The construction of a mercurial thermometer involves four different operations: (1) The choice of the tube; (2) The filling of the tube; (3) The determination of the fixed points of temperature; (4) The graduation of the thermometer.

(1.) The first object is to procure a tube of as uniform bore as possible. In order to ascertain whether this condition is fulfilled, a small column of mercury is introduced into the tube, and its length in different parts of the tube is measured. If these lengths are exactly equal, the tube must be of uniform bore. This is not generally the case, and we have to content ourselves with an approximation to this result; but we must reject tubes in which the differences of length observed are too great. When a suitable tube has been obtained, a reservoir is either blown at one end or attached by melting, the former plan being usually preferable.

(2.) After the tube has been chosen and the reservoir has been formed, a little cup is formed at the open end of the stem either of glass or of paper. This cup is partly filled with mercury (Figure 160). The stem is then held in a slightly inclined position, and the bulb is gently heated. The heat expands the air in the bulb, and drives out a part of it through the mercury in the cup. The bulb is now allowed to cool, the air in it contracts, and some of the mercury in the cup falls into the bulb to take the place of the air which has been expelled. The bulb is again heated so as to boil the mercury in it for a short time. As the mercury boils, its vapor drives the air completely out of the bulb and stem. The bulb is again allowed to cool, the vapor of mercury in the bulb and stem condenses, and the mercury from the cup passes into the bulb and stem so as completely to fill both. The bulb is now heated to a temperature a little above the highest temperature the thermometer is designed to measure, and while the bulb is still heated, the upper end of the stem is melted off, by means of a blowpipe, so as to close the stem air-tight. The thermometer is thus *sealed*. When the bulb is allowed to cool again, the mercury in the stem falls, leaving a vacuum above it.

Fig. 160.

(3.) The two fixed points of temperature are those at

which ice melts and water boils. The former is called the *freezing-point*, and the latter the *boiling-point*.

Under the same pressure it has been found that ice always melts at the same temperature, while the temperature at which water freezes varies somewhat with the conditions under which the experiment is tried. In order to determine the position of the freezing-point on the stem, the bulb and the lower part of the stem are surrounded by melting ice, contained in a perforated vessel so as to allow the water produced by the melting to escape (Figure 161). When the column in the stem ceases to fall, a mark is made on the tube, with a fine diamond, at the top of the mercurial column. This mark indicates the position of the freezing-point for this particular thermometer.

Fig. 161.

When water is boiling under the average atmospheric pressure, the temperature of the steam just over the water is found to be uniform, while that of the water varies somewhat with other circumstances than the pressure. In order to obtain the position of the boiling-point, the bulb and stem of the thermometer are enveloped in steam from boiling water, as shown in Figure 162. The height to which the mercury rises is then marked on the stem.

(4.) There are two thermometer *scales* in common use, namely, the *Fahrenheit* and the *Centigrade.* The ordinary scale in use in this country and in England is the Fahrenheit scale. On this scale the freezing-point is marked 32 and the boiling-point 212. The space between the freezing and boiling-points is divided into 180 equal parts, each of which is called a *degree.* These divisions are continued on the scale above the boiling-point and below the freezing-point to the ends of the tube. A Fahrenheit degree is $\frac{1}{180}$ of the difference of temperature between the freezing and boiling points.

On the Centigrade scale the freezing-point is marked 0 and the boiling-point 100, and the space between the two is divided into 100 equal parts, the divisions being continued to the ends of the tube. A Centigrade degree is $\frac{1}{100}$ of the difference of temperature between the freezing and boiling points. A Fahrenheit degree is $\frac{5}{9}$ of a Centigrade degree.

Fig. 162.

The zero of the Centigrade scale is the temperature of melting ice. The zero of the Fahrenheit scale is 32° F. below the melting-point of ice. It was the lowest temperature that Fahrenheit could obtain with a mixture of salt and ice.

204. *Alcohol Thermometers.* — Mercury freezes at a tem-

perature of about 40° below zero, or of — 40° F. Hence mercury cannot be used for measuring temperatures below that point. Low temperatures are sometimes measured by means of an *alcohol thermometer*. An alcohol thermometer is constructed in the same way as a mercurial thermometer, but the bulb is filled with alcohol instead of mercury. As alcohol boils at a temperature of about 175° F., an alcohol thermometer cannot be used for measuring high temperatures.

205. *Pyrometers*. — Mercury boils at a temperature of about 670° F. Hence a mercurial thermometer cannot be employed to measure temperatures above that point. Very high temperatures are often measured by the expansion of solids. The instrument used is called a *pyrometer*. One form of a pyrometer is shown in Figure 163. It consists

Fig. 163.

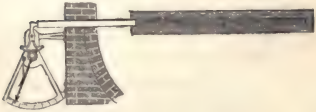
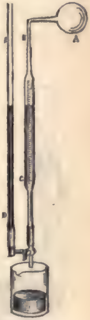


Fig. 164.



of a bar of iron lying in the groove of a porcelain slab. One end of the iron bar presses against the end of the groove, and the other end against the arm of an indicator. As the bar expands it moves the index point, the position of which indicates roughly the temperature to which the bar is exposed. Such pyrometers are not found to be very accurate.

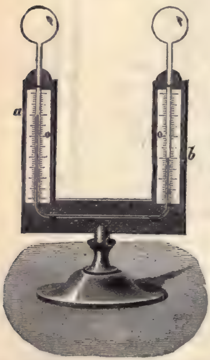
206. *Air Thermometer*. — The air thermometer, though somewhat troublesome to manage, is the most accurate of all thermometers. One form of this instrument is shown in Figure 164. The reservoir A of glass or porcelain is filled with air, and connects, by means of a narrow tube, with the upright tube $B\ C$, which is partially filled with mercury. The tube $B\ C$ con-

nects with a second tube DE open at the top and filled with mercury to the height of the mercury in BC, that the air in the reservoir may be subjected to the pressure of the atmosphere. The tube BC is graduated. When the reservoir A is heated, the air in it expands and drives the mercury down in the tube BC. By means of the stop-cock at the bottom, the mercury is kept at the same height in both tubes, that the pressure on the enclosed air may be always the same.

The globe A is made of glass unless the temperatures to be measured are above the melting-point of this substance, in which case the globe is of porcelain.

207. *Absolute Zero.* — If the air thermometer is constructed of a simple tube of uniform size throughout, without any enlargement at the end, and this tube is graduated in the same way as an ordinary mercurial thermometer, by first marking the freezing and boiling points on it, and then dividing the space between them into 180 equal parts, and continuing the divisions down to the closed end of the tube, it will be found that the last division will indicate — 459° F. This temperature is called *absolute zero*, and temperature measured from this point is called *absolute temperature* (119).

Fig. 165.



208. *Differential Thermometer.* — Leslie of Edinburgh invented, in the beginning of the present century, an ingenious instrument which enables us to measure small variations of temperature. A column of sulphuric acid, colored red, stands in the two branches of a bent tube, the extremities of which terminate in two globes of equal volume (Figure 165). When the air contained in the two globes is at the same temperature, whatever that temperature may be, the liquid, if the instrument is in order, stands at the same height

in the two branches. This point is marked zero. One of the globes being then maintained at a constant temperature, the other is raised through, for instance, 5 degrees, when the column rises on the side of the colder globe up to a point *a*, and descends on the other side to a point *b*. Suppose the space traversed by the liquid in each branch to be divided into 10 equal parts, each part will be equivalent to a quarter of a degree. This division is continued upon each branch on both sides of zero.

This *differential thermometer*, as it is called, is an instrument of great sensibility, and enabled Leslie to make some very delicate investigations on the subject of the radiation of heat. It is now, however, superseded by the *thermopile* invented by Melloni, and the *thermal balance* invented by Professor Langley. These instruments will both be described under the head of electricity.

C. Change of State.

I. FUSION AND SOLIDIFICATION.

209. *Fusing-Point.* — When any solid is sufficiently heated it will melt, but different solids melt at very different temperatures. The temperature at which any solid melts is called its *melting-point* or *fusing-point.* Mercury melts at — 40° F., ice at 32° F., lead at 608° F., and silver at 1832° F.

Most substances expand on melting, but a few, like ice, contract. When a substance expands on melting, an increase of pressure upon it will tend to hinder its melting, and will therefore raise its melting-point. When, on the other hand, the substance contracts on melting, an increase of pressure will tend to help its melting, and will accordingly lower its melting-point.

The passage from the solid to the liquid state is generally abrupt; but this is not always the case. Glass, for instance, before reaching a state of perfect liquefaction,

passes through a series of intermediate stages in which it is of a viscous consistency, and can be easily drawn out into exceedingly fine threads, or moulded into different shapes.

210. *Constant Temperature during Fusion.* — During the entire time of fusion the temperature remains constant. Thus, if a vessel containing ice is placed on the fire, the ice will melt more quickly as the fire is hotter; but if the mixture of ice and water is constantly stirred, a thermometer placed in it will indicate the temperature 32° without variation, so long as any ice remains unmelted; it is only after all the ice has become liquid that a rise of temperature will be observed.

In the same way, if sulphur is heated in a glass vessel, the temperature indicated by a thermometer placed in the vessel will rise gradually until it reaches about 230°, when a portion of the sulphur will melt; and if the vessel is shaken during the time of fusion, until the whole of the sulphur is liquefied, the temperature will remain steadily at this point.

211. *Latent Heat of Fusion.* — As we have just seen, all the heat that enters a body while it is undergoing fusion is employed in changing its state. The heat thus employed is said to be rendered *latent*, and is called the *latent heat of fusion*, or, since it exists in the latent state in the liquid formed, the *latent heat of the liquid.*

212. *Solidification.* — Were any substance sufficiently cooled, it would become solid. This conversion of a substance into a solid by a reduction of temperature is called *solidification*, or *congelation.*

It has been found that liquids can be cooled below the melting-point of their solids without congelation. Liquids thus cooled below their so-called freezing-points have, however, so to speak, a *tendency to freeze which is kept in check only by the difficulty of making a beginning.* If freezing once begins, or if ever so small a piece of the same substance in the frozen state is allowed to come in contact with the liquid, congelation

will quickly extend until there is none of the liquid left at a temperature below that of fusion. The condition of a liquid cooled below its freezing-point has been aptly compared to that of a row of bricks set on end in such a manner that if the first is overturned, it will cause all the rest to fall, each one overturning its successor.

The contact of its own solid infallibly produces congelation in a liquid in this condition, and the same effect may often be produced by the contact of some other solid, especially of a crystal, or by giving a slight jar to the containing vessel. In congelation, an amount of heat is always set free just equal to that rendered latent in the melting of the solid formed.

Fig. 166.

213. *Change of Volume in Congelation.* — In passing from the liquid to the solid state, bodies generally undergo a diminution of volume; there are, however, exceptions, such as ice, bismuth, silver, cast-iron, and type-metal. It is this property which renders these latter substances so well adapted for the purposes of casting, as it enables the metal to penetrate completely into every part of the mould. The expansion of ice is considerable, amounting to about $\frac{1}{14}$ of its bulk; its production is attended with enormous mechanical force, just as in the analogous case of expansion by heat.

Its effect in bursting water-pipes is well known. The following striking experiment was performed by Major

Williams at Quebec. He filled a 12-inch shell with water, and closed it with a wooden plug, driven in with a mallet. The shell was then exposed to the air, the temperature being — 18° F. The water froze, and the plug was projected to a distance of more than 100 yards, while a cylinder of ice of about 8 inches in length was protruded from the hole. In another experiment the shell split in halves, and a sheet of ice issued from the rent (Figure 166).

It is the expansion and consequent lightness of ice which enables it to float on the surface of the water, and to protect animal life beneath.

II. EVAPORATION AND CONDENSATION.

214. *Evaporation of Liquids.* — The majority of liquids, when left to themselves in contact with the atmosphere, gradually pass into the state of vapor and disappear. This phenomenon occurs much more rapidly with some liquids than with others, and those which evaporate most readily are said to be the most *volatile*. Thus, if a drop of ether is let fall upon any substance, it disappears almost instantaneously; alcohol also evaporates very quickly, but water requires a much longer time. The change is in all cases accelerated by an increase of temperature; in fact, when we *dry* a body before the fire, we are simply availing ourselves of this property of heat to hasten the evaporation of the moisture of the body. Evaporation may also take place from solids.

215. *The Terms Gas and Vapor.* — The words *gas* and *vapor* have no essential difference of meaning. A vapor is the gas into which a liquid is changed by evaporation. Every gas is probably the vapor of a certain liquid. The word *vapor* is especially applied to the gaseous condition of bodies, which are usually met with in the liquid or solid state, as water, sulphur, etc.; while the word *gas* generally denotes a body which, under ordinary conditions, is never

found in any state but the gaseous. When the air or any other gas contains all the vapor it can hold, it is said to be *saturated* with that vapor. The amount of vapor required to saturate a gas increases with the temperature. This may be shown by the following experiment. Pour a few drops of water into a glass flask, and then apply heat till the water is entirely evaporated and the flask appears dry. If the flask is allowed to cool, moisture will collect on its inner surface.

216. *Dry Air and Currents of Air favorable to Evaporation.* — The dryer the air the more rapid the evaporation, because the more readily the atmosphere will take up the vapor formed. Currents of air favor evaporation, because they prevent any layer of air from remaining long enough in contact with the liquid to become saturated with vapor. Other things being equal, wet clothes will dry much faster on a windy day than on a still day.

217. *Latent Heat of Evaporation.* — Evaporation is a cooling process. If a few drops of ether are allowed to fall on the hand, they will evaporate rapidly, and a sensation of cold will be experienced. If the bulb of a thermometer is dipped in ether and removed, the ether which adheres to it will quickly evaporate, and the mercury will fall several degrees. The heat consumed in evaporating a liquid is called the *latent heat of evaporation*, or the *latent heat of the vapor*.

218. *Ebullition.* — When a liquid contained in an open vessel is subjected to a continual increase of temperature, it is gradually changed into vapor, which is dissipated in the surrounding atmosphere. This action is at first confined to the surface; but after a certain time bubbles of vapor are formed in the interior of the liquid, which rise to the top, and set the entire mass in motion with more or less vehemence, accompanied by a characteristic noise; this is what is meant by *ebullition*, or *boiling*.

If we observe the gradual progress of this phenomenon, — for example, in a glass vessel containing water, — we shall perceive that after a certain time very minute bubbles are given off; these are bubbles of dissolved air. Soon after, at the bottom of the vessel, and at those parts of the sides which are most directly exposed to the action of the fire, larger bubbles of vapor are formed, which decrease in volume as they ascend, and disappear before reaching the surface. This stage is accompanied by a peculiar sound, indicative of approaching ebullition, and the liquid is said to be *singing*. The sound is probably caused by the collapsing of the bubbles as they are condensed by the colder water through which they pass. Finally, the bubbles increase in number, growing larger as they ascend, until they burst at the surface, which is thus kept in a state of agitation; the liquid is then said to *boil*.

219. *Difference between Evaporation at the Boiling-Point and below the Boiling-Point.* — Below the boiling-point evaporation takes place only at the surface; the *tension*, or elastic force, of the vapor is less than that of the atmosphere; and only a part of the heat received by the liquid is used in converting the liquid into vapor, the temperature of the liquid rising all the time that heat is applied to it. At the boiling-point evaporation takes place throughout the liquid; the tension of the vapor formed is equal to that of the atmosphere; and all the heat received by the liquid is used in converting it into steam, the temperature remaining stationary. The elastic force of the vapor given off by a liquid increases with the temperature, until we reach the boiling-point, when it equals that of the atmosphere. The boiling-point of a liquid is therefore the temperature at which the elasticity of the vapor is equal to the pressure of the atmosphere on the surface. It follows from this that the boiling-point must vary with the pressure. Under a pressure less than that of the atmosphere the boiling-point of water is below 212°; and under a greater pressure than that of the atmosphere is above 212°.

220. *Franklin's Experiment.* — Boil a little water in a flask long enough to expel all the air from the flask. Remove the flask from the source of heat and cork it securely. To render the exclusion of the air still more certain, the flask may be inverted with its corked end under water. Ebullition ceases almost instantly. Pour cold water over the flask (Figure 167) and the liquid will begin to boil, and will continue to do so for some time. The contact of the cold water with the flask lowers the temperature and tension of the steam which presses on the surface of the water, and the diminution of pressure allows the water to boil at a lower temperature.

Fig. 167.

Fig. 168.

221. *The Hypsometer.* — The *hypsometer* (Figure 168) is an instrument used for ascertaining the height of mountains by means of the boiling-point of water. It consists of a little boiler heated by a spirit-lamp, and terminating in a telescopic tube with an opening at the side through which the steam escapes. A thermometer dips into the steam, and projects through the top of the tube so as to allow the temperature of ebullition to be read. From the boiling-point as indicated by the hypsometer, the pressure of the atmosphere can be ascertained, and from this the height of the mountain, in the same way as with the barometer.

222. *Papin's Digester.* — In a confined vessel water may be raised to a higher temperature than would be possible in the open air, but it will not boil. This is the case in the apparatus invented by the celebrated Papin, and called after him *Papin's digester* (Figure 169). It is a bronze vessel of great strength, covered with a lid secured by a powerful screw. It is employed for raising water to very high temperatures, and thus obtaining effects which would not be possible with water at 212°, such, for example, as dissolving the gelatine contained in bones.

Fig. 169.

It is to be observed that the tension of the steam increases rapidly with the temperature, and may finally acquire an enormous power. Thus, at 392°, the pressure is that of 16 atmospheres, or about 240 pounds on the square inch. In order to obviate the risk of explosion, Papin introduced a device for preventing the pressure from exceeding a definite limit. This invention has since been applied to the boilers of steam-engines, and is well known as the *safety-valve.* It consists of an opening, closed by a conical valve or stopper, which is pressed down by a lever loaded with a weight. Suppose the area of the lower end of the stopper to be 1 square inch, and that the pressure is not to exceed 10 atmospheres, corresponding to a temperature of 356°. The magnitude and position of the weight are so arranged that the pressure on the whole is 10 times 15 pounds. If the tension of the steam exceeds 10 atmospheres, the lever will be raised, the steam will escape, and the pressure will be thus relieved.

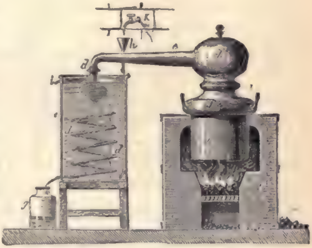
223. *Condensation of Vapors.* — *Condensation*, or the conversion of a vapor into a liquid, is the reverse of evaporation. In condensation, the heat rendered latent

in evaporation is again set free as sensible heat. As an increase of temperature and a diminution of pressure promote evaporation, so a diminution of temperature and an increase of pressure promote condensation.

224. *Distillation.* — *Distillation* consists in boiling a liquid and condensing the vapor evolved. It enables us to separate a liquid from the solid matter dissolved in it, and to effect a partial separation of the more volatile constituents of a mixture from the less volatile.

The apparatus employed for this purpose is called a *still.* One of the simpler forms, suitable for distilling water, is shown in Figure 170.

Fig. 170.



It consists of a retort *a*, the neck of which *c* communicates with a spiral tube *d d*, called the *worm*, placed in the vessel *e*, which contains cold water. The water in the retort is raised to ebullition, the steam given off is condensed in the worm, and the *distilled water* is collected in the vessel *g*.

As the condensation of the steam proceeds, the water of the cooler becomes heated, and must be renewed. For this purpose a tube descending to the bottom of the cooler is supplied with a continuous stream of cold water from above, while the superfluous water flows out by the tube *i* at the upper part of the cooler. In this way the warm water, which rises to the top, is continually removed.

225. *The Molecular Theory of Evaporation and Condensation.* — The following account of the molecular theory of evaporation and condensation is taken from Maxwell: "We have seen that in the case of a gas some of the molecules have a much greater velocity than others, so that it is only to the average velocity of all the molecules that we can ascribe a definite value.

It is probable that this is also true of the motions of the molecules of a liquid, so that, though the average velocity may be much smaller than in the vapor of that liquid, some of the molecules in the liquid may have velocities equal to or greater than the average velocity in the vapor. If any of the molecules at the surface of the liquid have such velocities, and if they are moving *from* the liquid, they will escape from those forces which retain the other molecules as constituents of the liquid, and will fly about as vapor in the space outside the liquid. This is the molecular theory of evaporation. At the same time, a molecule of the vapor striking the liquid may become entangled among the molecules of the liquid, and may thus become part of the liquid. This is the molecular explanation of condensation. The number of molecules which pass from the liquid to the vapor depends on the temperature of the liquid. The number of molecules which pass from the vapor to the liquid depends upon the density of the vapor as well as its temperature. If the temperature of the vapor is the same as that of the liquid, evaporation will take place as long as more molecules are evaporated than condensed; but when the density of the vapor has increased to such a value that as many molecules are condensed as evaporated, then the vapor has attained its maximum density. It is then said to be saturated, and it is commonly supposed that evaporation ceases. According to the molecular theory, however, evaporation is still going on as fast as ever; only, condensation is also going on at an equal rate, since the proportions of liquid and of gas remain unchanged."

Fig. 171.

226. *Spheroidal State.* — This is the name given to a peculiar condition which is assumed by liquids when exposed to the action of very hot metals.

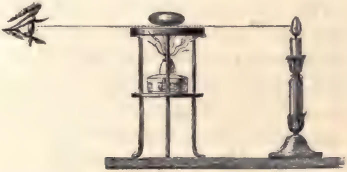
If we take a smooth plate of iron or silver, and let fall a drop of water upon it, the drop will evaporate more rapidly as the temperature of the plate is increased up to a certain point. When the temperature of the

plate exceeds this limit, which, for water, appears to be about 300°, the drop assumes a spheroidal form, rolls about like a ball or spins on its axis, and frequently exhibits a beautiful rippling, as represented in Figure 171. While in this condition it evaporates much more slowly than when the plate was at a lower temperature. If the plate is allowed to cool, a moment arrives when the globule of water flattens out, and boils rapidly away with a hissing noise.

If the temperature of the liquid is measured by means of a thermometer with a very small bulb, it is always found to be below the boiling-point.

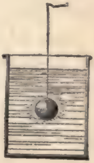
In the spheroidal state the liquid and the metal plate do not come into contact. This fact can be proved by direct observation.

Fig. 172.



The plate used must be quite smooth and accurately levelled. When the plate is heated, a little water is poured upon it and assumes the spheroidal state. By means of a fine platinum wire which passes into the globule, the liquid is kept at the centre of the metal plate. It is then very easy, by placing a light behind the globule, to see distinctly the space between the liquid and the plate (Figure 172).

Fig 173.



This separation is maintained by the rush of steam from the under surface of the globule, which is also the cause of the peculiar movements above described. In consequence of the separation, heat can pass to the globule only by radiation, and hence its comparatively low temperature is accounted for.

The absence of contact between a liquid and a metal at high temperature may be shown by

several experiments. If, for instance, a ball of platinum is heated to bright redness, and plunged (Figure 173) into water, the liquid is seen to recede on all sides, leaving an envelope of vapor around the ball. This latter remains red for several seconds, and contact does not take place till its temperature has fallen to about 300°. Violent ebullition then takes place.

D. Measurement of Heat.

227. *The Unit of Heat.* — The temperature of a body indicates its thermal condition, but not the amount of heat in it. The thermometer shows a pound of iron and ten pounds of iron to be of the same temperature, when, of course, the latter has ten times as much heat in it as the former. In the measurement of heat there is needed some unit in which amounts of heat can be expressed. The English *unit of heat* is the amount of heat required to raise one pound of water at 32° one degree in temperature.

228. *Specific Heat.* — If equal bulks of water and of mercury are exposed to the same source of heat, it will be found that the temperature of the mercury will rise faster than that of the water, though the mercury is more than 12 times as heavy as the water. It has been found that it requires very different amounts of heat to raise the same weight of different substances one degree in temperature.

The *specific heat* of a substance is the amount of heat required to raise one pound of it one degree in temperature. The specific heat of water is 1, and it is higher than that of any other substance, with the single exception of hydrogen.

229. *A Body in Cooling 1° gives out just as much Heat as it takes to Heat it 1°.* — Boil a quarter of a pound of water in a beaker, and the bulb of a thermometer plunged into it will indicate a temperature of 212°. Remove the beaker from the source of heat, and pour the water into another beaker containing a quarter of a pound of water

of a temperature of 70°. Stir the mixture a short time with the bulb of a delicate thermometer, and the temperature will be found to be 141°. The first quarter of a pound of water has then lost 71°, and the second has gained 71°; in other words, the first in cooling 1° has given out just heat enough to warm the second 1°. The same is true of all other bodies.

230. *The Water Calorimeter.* — A *calorimeter* is an instrument for measuring quantities of heat. The *water calorimeter* is a vessel containing water into which a heated substance may be introduced. As the substance cools it imparts some of its heat to the water, and the amount of heat given up by the substance may be calculated from the weight of the water in the calorimeter and the number of degrees the temperature is raised. The number of units of heat received by the water will be equal to the product of the rise of temperature in degrees and the weight of the water in pounds.

The rise of temperature can be ascertained by noting the temperature at the beginning and at the end of the experiment. Allowance must be made for the heat which escapes from the water during the experiment. This method of measuring heat is called the *method of mixture.*

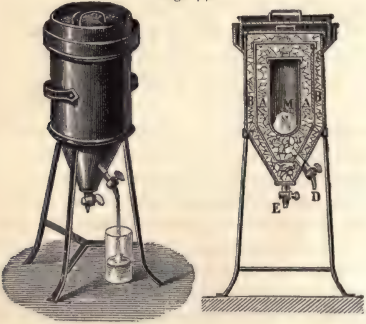
To find the specific heat of a substance by this method, weigh the substance to be tried, raise its temperature to a known point, and plunge it into the calorimeter. Note the temperature of the water at the beginning and end of the experiment, and calculate the amount of heat given to the water by the substance in cooling. The temperature of the water at the end of the experiment will show how many degrees the substance has cooled. Divide the number of units of heat which the substance imparts to the water in cooling by the number of degrees the substance has cooled, and the quotient will be the amount of heat given out by the substance in cooling one degree. Divide the last amount by the weight of the substance in pounds

or fractions of a pound, and the quotient will be the amount of heat that would be given out by one pound of the substance in cooling one degree. This is the *specific heat* of the substance.

231. *The Latent Heat of Water.* — By the *latent heat of water* we mean the amount of heat required to melt a pound of ice. It is 143 units.

The latent heat of water can be found by a process the reverse of that given above. The calorimeter is first filled with water at 212°. We will suppose it to hold ten pounds of water. A piece of ice, weighing say a pound, is put into the calorimeter. The water will impart heat to the ice, which will quickly melt. The resulting temperature will be $182\frac{7}{11}$ degrees. The ten pounds of water have fallen $29\frac{4}{11}$ degrees in temperature, and imparted to the ice $293\frac{7}{11}$ units of heat. This heat has melted the ice, and raised the temperature of the pound of water formed from 32° to $182\frac{7}{11}$ degrees, that is, $150\frac{7}{11}$ degrees. To do the latter requires $150\frac{7}{11}$ units. The amount of heat deducted from $293\frac{7}{11}$ units leaves 143 units as the amount of heat used in melting the pound of ice. Hence the latent heat of water is 143 units.

Fig. 174.



232. *The Ice Calorimeter.* — Another method of finding specific heat is by melting ice. The substance is first

weighed, then heated to a certain temperature, as 100°, and placed in the vessel *M* (Figure 174). This vessel is placed within the vessel *A*, the space between the two being filled with ice. The vessel *A* is placed in another, *B*, from which it is also separated by ice. Since the vessel *A* is surrounded by ice, the heat which melts the ice within it must come wholly from the vessel *M*. As the ice in *A* melts the water runs off through the pipe *D*. As we know how much heat is required to melt one pound of ice, we need only know how much ice is melted by any substance within the box *M*, in order to find how many units of heat it has given up. Dividing this by the weight of the substance and by the number of degrees it has cooled, we get its specific heat.

Thus, suppose ten pounds of iron heated to 132° are placed in *M*, and allowed to cool 100°; and that the iron is found to give out 109 units of heat. Then, $109 \div 10 = 10.9$, which is the number of units of heat which would be given out by one pound cooling 100°; and $10.9 \div 100 = .109$, which is the number of units one pound would give out in cooling 1°, or the specific heat of iron.

233. *The Latent Heat of Steam.* — The latent heat of steam may be found by allowing a quantity of steam to pass into a water calorimeter. The steam will be condensed, and the water formed will be cooled to the resulting temperature of the water in the calorimeter. The heat given out in this condensation and cooling will raise the temperature of the water in the calorimeter. The amount of this heat may be calculated as in a previous case. We can also calculate the amount of heat that is given out in the cooling of the water formed from the steam. The difference between these two amounts will be the amount of heat set free in the condensation of the steam. This, divided by the weight of the steam, will give the latent heat of steam, which is 967 units. The latent heat

of watery vapor is higher than that of any other known vapor.

QUESTIONS ON TEMPERATURE AND HEAT.

102. Oil of vitriol freezes at $-30°$ F. This is equivalent to what temperature on the Centigrade scale? The absolute scale?

103. Lead melts at 620° F. At what temperature does lead melt on the Centigrade scale and on the absolute scale?

104. Iron melts at 2800° F. What is the equivalent temperature on the Centigrade scale and on the absolute scale?

105. What temperatures on the Fahrenheit and absolute scales correspond to 50° C.? To $-25°$ C.? To 380° C.?

106. The specific heat of iron is .109. How many units of heat would it take to raise 30 pounds of iron 75° F.?

107. The specific heat of silver is .055. How many units of heat would be given out by $\frac{1}{6}$ of a pound of silver in cooling 320° F.?

108. The specific heat of mercury is .033. How much heat would it take to raise 23 pounds of mercury 125° F.?

109. How much heat would it take to melt a cubic yard of ice, the specific gravity of ice being .96?

110. How much heat would be given out by the condensation of 25 pounds of steam at a temperature of 212° F.?

111. How much heat would it take to convert a cubic yard of water into steam at a temperature of 212° F.?

II.

RELATIONS BETWEEN HEAT AND WORK.

234. *Heat consumed in the Performance of Work.* — In expansion, liquefaction of solids, and evaporation, the molecules are always pushed into new positions against some kind of resistance, either internal or external; that is to say, work is done upon the molecules. This work is always done at the expense of heat, either of that already in the body or of that communicated to the body. Hence, whenever any of these kinds of work are done without the

application of heat to the body, some of the heat in the body is consumed and its temperature falls; and whenever the work is done by the application of heat, the temperature of the body rises less than it would with the same application of heat were no work done.

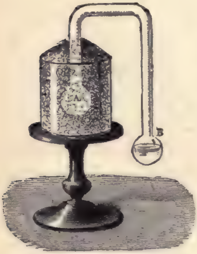
235. *Heat consumed in Expansion.* — If a thermometer bulb is introduced into the receiver of an air-pump through an opening at the top of the receiver, into which the stem of the thermometer is fitted air-tight by means of a rubber cork, and the pump is worked, as the exhaustion proceeds the air in the receiver will expand more and more, and the mercury in the stem of the thermometer will fall several degrees, indicating a reduction of temperature. The air is always chilled when any expansion takes place in it without the application of heat.

It takes 6.7 units of heat to raise the temperature of a cubic foot of air 490° when the air is confined so that it cannot expand, and 9.5 units to raise the temperature the same amount when the air is free to expand. In the latter case the air will expand enough to double its volume. So that 2.8 units of heat are consumed in expanding a cubic foot of air enough to double its volume. The heat consumed in expansion is called the *latent heat of expansion.* The conversion of sensible into latent heat is simply the transformation of kinetic into potential energy. When the air contracts again, the potential energy is transformed again into kinetic energy, and the latent heat again becomes sensible.

236. *Heat consumed in Liquefaction.* — Place some pulverized nitrate of ammonia in a small beaker glass, add an equal bulk of water, and stir the mixture with the bulb of a thermometer. The solid will be rapidly dissolved, and the temperature of the mixture will quickly fall 40 or 50 degrees. The mixture is chilled to such an extent that, if put upon a wet board, the beaker will be quickly frozen

to it. In the liquefaction of a solid a part of its kinetic energy is transformed into potential energy, and sensible heat becomes latent heat. In the solidification of the liquid, the potential energy is transformed back again into kinetic energy, and the latent heat again becomes sensible heat.

Fig. 175.



In the melting of a solid, all the kinetic energy that enters the body is transformed into potential energy by the conversion of the solid into a liquid, and hence there is no rise of temperature while the solid is melting.

237. *Heat consumed in Evaporation.* — The consumption of heat in evaporation may be illustrated by means of the *cryophorus* (Figure 175). It consists of a bent tube with a bulb at each end. It is partly filled with water, and hermetically sealed while the liquid is in ebullition, thus expelling the air. When an experiment is to be made, all the liquid is passed into the bulb *B*, and the bulb *A* is plunged into a freezing mixture, or into pounded ice. The cold condenses the vapor in *A*, and thus produces rapid evaporation of the water in *B*. In a short time needles of ice appear on the surface of the liquid.

If a little water is poured into a small test-tube, which is placed in a wine-glass of ether (Figure 176), and a current of air is blown through the ether by means of a pair of bellows, the rapid evaporation of the ether will reduce the temperature sufficiently to freeze the water in the tube in a short time.

In evaporation as in liquefaction, the conversion of sensible into latent heat is merely the transformation of kinetic energy into potential energy.

238. *Freezing Mixture.* — The ordinary *freezing mixture* is a mixture of salt and ice. The salt causes some of the ice to liquefy, and this liquefaction of the ice consumes so much heat that the temperature of the mixture is reduced sufficiently to freeze cream within a can which is surrounded by the mixture.

Fig. 176.

A mixture of solidified carbonic acid and ether, in the receiver of an air-pump from which the air has been exhausted so as to promote the evaporation, evaporates with very great rapidity, and the consumption of heat is so great as to reduce the temperature of the mixture to $-166°$ F.

A mixture of solidified nitrous oxide and bisulphide of carbon, under similar circumstances, evaporates still more rapidly, and reduces the temperature to $-220°$ F.

239. *Manufacture of Ice.* — Ice is now manufactured on a large scale in Southern cities, by means of liquefied ammonia gas. The liquefied gas is passed into pipes similar to gas-pipes, and then allowed to evaporate by diminishing the pres-

sure. The pipes are bent around so as to form rectangular coils, within which are placed the cans of water to be frozen. The rapid evaporation of the liquefied ammonia within the pipes reduces the temperature of the coils sufficiently to freeze the water within the cans.

If the pipes run to and fro horizontally under the surface of water in a large tank, a continuous sheet of ice may be formed in midsummer.

240. *Solidification of Gases.* — If any gas is liquefied by the combined action of cold and pressure, and then

Fig. 177.

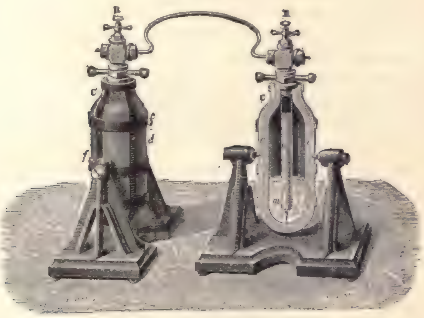
allowed to escape into the atmosphere in a fine stream, so as to evaporate freely, the temperature will be reduced to such an extent that a portion of the vapor will be frozen, so that the gas can be obtained in a solid state.

In the case of hydrogen, and some other gases, which cannot be liquefied by the direct action of cold and pressure, if the gas is reduced to the greatest possible degree of density by the combined action of cold and pressure, and then is allowed to expand by a sudden removal of the pressure, the sudden expansion chills the gas sufficiently

to freeze a portion of it. Hydrogen frozen in this way is heard to rattle like hail when it falls on the table.

241. *Faraday's Method of Liquefying Gases.* — Most gases may be liquefied by the combined action of cold and pressure. Faraday was the first who conducted methodical experiments in the liquefaction of gases. The apparatus at first employed by him is shown in Figure 177. It consists of a very strong bent glass tube, closed at both ends. One end of this contains the ingredients which, on the application of heat, evolve the gas to be tried, while the other is immersed in a freezing mixture. The pressure produced by the evolution of the gas in large

Fig. 178.



quantity in a confined space combines with the cold of the freezing mixture to produce liquefaction of the gas, and the liquid accordingly collects in the cold end of the tube.

242. *Thilorier's Method of Liquefying Carbonic Acid Gas.* — Thilorier, about the year 1834, invented the apparatus shown in Figure 178, which is based on this method of Faraday, and is intended for liquefying carbonic acid gas. This operation requires the enormous pressure of about fifty atmospheres at ordinary temperatures. If a slight rise of temperature occurs from the chemical action attending the production of the gas, a pressure of 75 or 80 atmospheres may not improbably be re-

quired; hence great care is necessary in testing the strength of the metal employed in the construction of the apparatus. This was formerly made of cast-iron, and strengthened by wrought-iron hoops; but the construction has since been changed, on account of a terrible explosion, which cost the life of one of the operators. At present, the vessels are formed of three parts: the inner one of lead; the next *e*, which completely envelops this, of copper; and, finally, the hoops *ff* of wrought-iron, which bind the whole together. The apparatus consists of two distinct reservoirs. In the generator *C* is placed bicarbonate of soda, and a vertical tube *a*, open at the top, containing sulphuric acid. By imparting an oscillatory movement to the vessel about the two pivots which support it near the middle, the sulphuric acid is gradually spilt, and carbonic acid is evolved, which becomes liquid in the interior. The generator is then connected with the condenser *C'* by the tube *t*, and the stopcocks *R* and *R'* are opened. As soon as the two vessels are in communication, the liquid carbonic acid passes into the condenser, which is at a lower temperature than the generator, and represents the cold branch of Faraday's apparatus. The generator can then be disconnected and recharged, and thus several pints of liquid carbonic acid may be obtained. In the foregoing methods the pressure which produces liquefaction is furnished by the evolution of the gas itself.

243. *The Critical Temperature of Gases.* — Dr. Andrews, by a series of elaborate experiments on carbonic acid, with the aid of an apparatus which permits the pressure and temperature to be altered independently of each other, has shown that at temperatures above 88° F. this gas cannot be liquefied, but, when subjected to intense pressure, becomes reduced to a condition in which, though homogeneous, it is neither a liquid nor a gas. When in this condition, lowering of temperature under constant pressure will reduce it to a liquid, and diminution of pressure at constant temperature will reduce it to a gas; but in neither case can any breach of continuity be detected in the transition.

On the other hand, at temperatures below 88° F., the substance remains completely gaseous until the pressure reaches a certain limit depending on the temperature, and any pressure exceeding this limit causes liquefaction to begin and to continue

till the whole of the gas is liquefied, the boundary between the liquefied and unliquefied portions being all the while sharply defined.

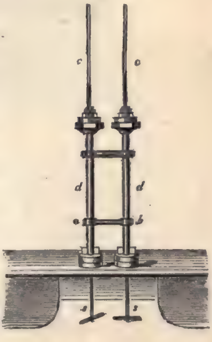
The temperature of 88° may therefore be called the *critical* temperature for carbonic acid; and it is probable that every other substance, whether usually occurring in the liquid or gaseous state, has in like manner its own critical temperature, above which it is impossible to convert the gas into a liquid by any amount of pressure.

When a substance is a little above its critical temperature, and occupies a volume which would, at a lower temperature, be compatible with partial liquefaction, very great changes of volume are produced by very slight changes of pressure.

On the other hand, when a substance is at a temperature a little below its critical point, and is partially liquefied, a slight increase of temperature leads to a gradual obliteration of the surface of demarcation between the liquid and the gas; and when the whole has been thus reduced to a homogeneous fluid, it can be made to exhibit an appearance of moving or flickering striæ throughout its entire mass by slightly lowering the temperature, or suddenly diminishing the pressure.

The apparatus employed in these remarkable experiments is shown in Figure 179, where *c c* are two capillary glass tubes of great strength, one of them containing the carbonic acid, or other gas to be experimented on, the other containing air to serve as a manometer. These are connected with strong copper tubes *d d*, of larger diameter, containing water, and communicating with each other through *a b*, the water being separated from the gases by a column of mercury occupying the lower portion of each capillary tube. The steel screws *s s* are the instruments for applying pressure. By screwing either of them forward into the water, the contents of both tubes

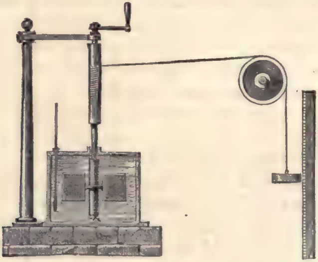
Fig. 179.



are compressed, and the only use of having two is to give a wider range of compression. A rectangular brass case (not shown in the figure), closed before and behind with plate-glass, surrounds each capillary tube, and allows it to be maintained at any required temperature by the flow of a stream of water.

244. *Mechanical Equivalent of Heat.* — Meyer found the equivalent of a unit of heat in foot-pounds, by converting heat into mechanical energy through the expansion of air. In the expansion of air the work done is wholly external, namely, that of pushing aside the surrounding air. We have seen that it takes 2.8 units of heat to expand a cubic foot of air to double its volume. To ascertain the amount of work done in pushing away

Fig. 180.



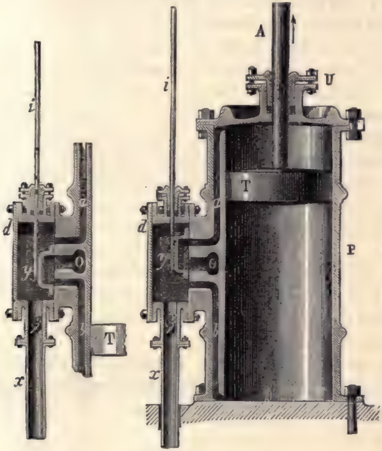
the surrounding air, Meyer imagined his cubic foot of air at the bottom of a prismatic box whose section was a foot square, so that the air could expand only upward. The upper surface of the cubic foot of air contains 144 square inches. Hence the weight of the column of air pressing upon this surface is about $144 \times 15 = 2160$ pounds; and when the cubic foot of air expands so as to double its volume, this weight must be raised one foot high. Hence 2.8 units of heat are equivalent to 2160 foot-pounds of mechanical energy, and one unit of heat to 772 foot-pounds, nearly. This number of foot-pounds is the *mechanical equivalent of heat.*

245. *Joule's Method of finding the Mechanical Equivalent of Heat.* — Joule ascertained the mechanical equivalent of heat

by converting mechanical energy into heat by means of friction. He arranged his apparatus so that he could measure both the mechanical energy employed and the heat produced.

He constructed an agitator, which is somewhat imperfectly represented in Figure 180, consisting of a vertical shaft, carrying several sets of paddles revolving between stationary vanes, these latter serving to prevent the liquid in the vessel from being bodily whirled in the direction of rotation. The vessel

Fig. 181.



was filled with water, and the agitator was made to revolve by means of a cord, wound round the upper part of the shaft, carried over a pulley, and attached to a weight, which by its descent drove the agitator, and furnished a measure of the work done. The pulley was mounted on friction-wheels, and the weight could be wound up without moving the paddles. When all corrections had been applied, it was found that the heat communicated to the water by the agitation amounted to one unit for

every 772 foot-pounds of work spent in producing it. This result was verified by various other forms of experiment, and may be assumed to be correct within about one foot-pound.

246. *The Cylinder of the Steam-Engine.* — The molecular energy of heat can be made to do mechanical work by means of the arrangement shown in Figure 181. The steam derives its expansive power from the heat, and this expansive power is made to work a piston in the cylinder of the steam-engine. The steam from the boiler passes through the tube x into the *steam-box d.* Two pipes run from this box, one a to the top and the other b to the bottom of the cylinder. A sliding-valve y is so arranged as always to close one of the pipes to the steam-box and open it to the *exit-pipe O;* and, at the same time, to open the other pipe to the steam-box and close it to the exit-pipe. In the right-hand figure, the lower pipe b is open, and the steam can pass in under the piston and force it up At the same time the steam which has done its work on the other side of the piston passes out from the cylinder through the pipes a and O.

The sliding-valve is connected by means of the rod i with the crank of the engine, so that it moves up and down as the piston moves down and up. As soon, then, as the piston has reached the top of the cylinder, the sliding-valve is brought into the position shown in the left-hand figure. The steam now passes into the cylinder above the piston through the pipe a, and forces the piston down, and the steam on the other side which has done its work goes out through b and O. The sliding-valve is now again in the position shown in the right-hand figure, and the piston is driven up again as before; and thus it keeps on moving up and down, or in and out.

III.

DISTRIBUTION OF HEAT.

A. Conduction.

247. *Illustration of Conduction.* — If heat is applied to one end of a bar of metal, it is slowly propagated through the substance of the bar, producing a rise of temperature

which is first perceptible near the heated end, and afterwards in more remote portions. The transmission of heat from molecule to molecule through the substance of the body is called *conduction*. If the application of heat to one end of the bar is continued for a sufficiently long time, and with great steadiness, the different portions of the bar will at length cease to rise in temperature, and will retain steadily the temperatures which they have acquired. We may thus distinguish two stages in the experiment: 1st, the *variable* stage, during which all portions of the bar are rising in temperature; and, 2d, the *permanent* state, which may subsist for any length of time without alteration. In the former, the bar is gaining heat; that is, it is receiving more heat from the source than it gives out to surrounding bodies. In the latter, the receipts and expenditure of heat are equal, and are equal not only for the bar as a whole, but for every small portion of which it is composed.

In the permanent state no further accumulation of heat takes place. All the heat which reaches an internal particle is transmitted by conduction, and the heat which reaches a superficial particle is given off partly by radiation and air-contact, and partly by conduction to colder neighboring particles. In the earlier stage, on the contrary, only a portion of the heat received by a particle is thus disposed of, the remainder being accumulated in the particle, and serving to raise its temperature.

In order to obtain results depending on conduction free from the complications arising from differences of specific heat, we must, in all cases, wait for the permanent state. In the earlier stage great specific heat acts as an obstacle to rapid transmission, and a body of great specific heat would be liable to be mistaken for a body of small conductivity.

248. *Difference of Conductivity.* — The following experi-

ments are often adduced in illustration of the different conducting powers of different solids.

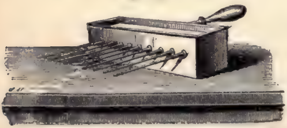
Two bars of the same size, but of different materials

Fig. 182.

(Figure 182), are placed end to end, and small wooden balls are attached by wax to their under surfaces at equal distances. The bars are then heated at their contiguous ends, and, as the heat extends along them, the wax melts, and the balls successively drop off. If the heating is continued till the permanent state arrives, it may generally be concluded that the bar which has lost most balls is the best conductor.

The well-known experiment of Ingenhousz is of the same kind. The apparatus (Figure 183) consists of a copper box having in one of its faces a row of holes, in which rods of different materials can be fixed. The rods having been previously coated with wax, the box is filled with boiling water, which comes in contact with the inner ends of the rods. The wax gradually melts as the heat travels along the rods; and if the experiment is continued till the melting reaches its limit, those rods on which it has extended furthest are, generally speaking, the best conductors. It is thus found that different metals are not equally good conductors of heat, and that the more familiar ones may be arranged in the

Fig. 183.



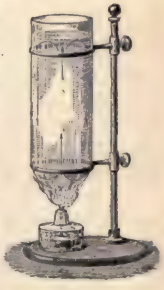
following order, beginning with the best conductors: *Silver, copper, gold, brass, tin, iron, lead, platinum, bismuth.*

In both these experiments we must beware of attempting to measure conductivity by the quickness with which the melting advances. This quickness may be simply an indication of small specific heat.

249. *Conducting Power of Metals.* — Metals, though differing considerably one from another, are as a class greatly superior in conductivity to other substances, such as wood, marble, brick, etc. This explains several familiar phenomena. If the hand is placed upon a metal plate at the temperature of 10° C., or plunged into mercury at this temperature, a very marked sensation of cold is experienced. This sensation is less intense with a block of marble at the same temperature, and still less with a piece of wood. The reason is that the hand, which is at a higher temperature than the substance to which it is applied, gives up a portion of its heat, which is conducted away by the substance; consequently a larger portion of heat is parted with, and a more marked sensation of cold experienced, in the case of the body of greater conducting power.

250. *Conducting Powers of Liquids.* — With the exception of mercury and other melted metals, liquids are exceedingly bad conductors of heat. This can be shown by heating the upper part of a column of liquid, and observing the variations of temperature below. These will be found to be scarcely perceptible, and to be very slowly produced. If the heat were applied below (Figure 184) we should have the process called *convection* of heat; the lower layers of liquid would rise to the sur-

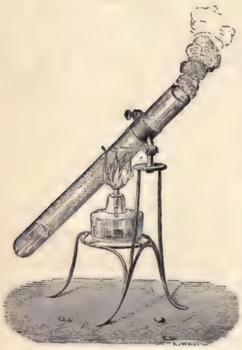
Fig. 184.



face, and be replaced by others, which would rise in their turn, thus producing a circulation and a general heating of the liquid. On the other hand, when heat is applied above, the expanded layers remain in their place, and the rest of the liquid can be heated only by conduction and radiation.

The following experiment is an illustration of the very feeble conducting power of water. A piece of ice is placed at the bottom of a glass tube (Figure 185), which is then partly filled with water; heat is applied to the middle of the tube, and the upper portion of the water is readily raised to ebullition, without melting the ice below.

Fig. 185.



251. *Conducting Power of Gases.* — Of the conducting power of gases it is almost impossible to obtain any direct proofs, since it is exceedingly difficult to prevent the interference of convection and direct radiation. We know, however, that they are exceedingly bad conductors. In fact, in all cases when gases are enclosed in small cavities where their movement is difficult, the system thus formed is a very bad conductor of heat. This is the cause of the feeble conducting powers of many kinds of cloth, of fur, eider-down, felt, straw, saw-dust, etc. Materials of this kind, when used as articles of clothing, are commonly said to be *warm*, because they hinder the heat of the body from escaping. If a garment of eider-down or fur were compressed so as to expel the greater part of the air, and to reduce the substance to a thin sheet, it would be found to be a

much less warm covering than before, having become a better conductor. We thus see that it is the presence of air which gives these substances their feeble conducting power, and we are accordingly justified in assuming that air is a bad conductor of heat.

B. Convection.

252. *Convection Currents.* — Although liquids and gases are very poor conductors of heat, they allow heat to be distributed through them readily by *convection currents.* When heat is applied to any portion of a fluid, the heated portion expands, becomes lighter, and rises, allowing colder portions to take its place and become heated in turn. When any portion of a fluid is maintained at a higher temperature than the surrounding portion, the system of currents shown by the arrows in Figure 184 is always formed. There will be an upward current at the centre of the heated region, an outflow in every direction above, downward currents on every side, and an inflow from every direction below. It is chiefly by such convection currents that heat is distributed through liquids and gases.

C. Radiation and Absorption.

253. *Illustrations of Radiation.* — When two bodies at different temperatures are brought opposite to each other, an unequal exchange of heat takes place through the intervening distance; the temperature of the hotter body falls, while that of the colder rises, and after some time the temperature of both becomes the same. This propagation of heat across an intervening space is what is meant by *radiation*, and the heat transmitted under these conditions is called *radiant heat.* Instances of heat communicated by radiation are the heat of a fire received by a person sitting in front of it, and the heat which the earth receives from the sun.

254. *Radiations will traverse a Vacuum.* — This last instance shows us that radiation as a means of propagating heat is independent of any ponderable medium. But since the solar heat is accompanied by light, it might still be questioned whether dark heat could in the same way be propagated through a vacuum.

This was tested by Rumford in the following way. He constructed a barometer (Figure 186), the upper part of which was expanded into a globe, and contained a thermometer hermetically sealed into a hole at the top of the globe, so that the bulb of the thermometer was at the centre of the globe. The globe was thus a Torricellian vacuum-chamber. By melting the tube with a blow-pipe, the globe was separated, and was then immersed in a vessel containing hot water, when the thermometer was immediately observed to rise to a temperature higher than could be due to the conduction of heat through the stem. The heat had therefore been communicated by direct radiation through the vacuum between the sides of the globe and the bulb *a* of the thermometer.

Fig. 186.

255. *Radiant Heat travels in Straight Lines.* — In a uniform medium the radiation of heat takes place in straight lines. If, for instance, between a thermometer and a source of heat there are placed several screens, each pierced with a hole, and if the screens are so arranged that a straight line can be drawn through the holes from the source to the thermometer, the temperature of the latter immediately rises; if a different arrangement is adopted, the heat is stopped by the screens, and the thermometer indicates no effect.

The heat which travels along any one straight line is

called a *ray* of heat. Thus, we say that rays of heat issue from all points of the surface of a heated body, or that such a body emits rays of heat.

256. *Molecular Theory of Radiation.* — According to the molecular theory, radiations originate in the vibrations of the atoms within the molecule. Each kind of atoms seems to have certain characteristic rates of vibration, and when the molecules in their motions come into collision, their atoms are thrown into vibration; these vibrations are communicated to the surrounding ether, and are propagated through the ether in minute waves and with an enormous velocity. As the temperature of the body rises the agitation of its molecules becomes more energetic, and the more violent collisions of the molecules produce more powerful vibrations of the atoms. Hence the radiation becomes more intense as the temperature rises.

257. *Different Kinds of Radiation.* — At low temperatures bodies emit only *obscure* radiations. When the temperature reaches a certain point, the body becomes red-hot, and begins to emit *luminous* radiations. At a still higher temperature it becomes white-hot.

258. *Diathermanous Bodies.* — A body, like air, which will allow thermal rays to pass readily through it is said to be *diathermanous.* If a polished plate of glass is held in front of a body heated to dull redness, it will stop nearly all the heat emitted by it. If the same plate of glass is held in front of a body at bright white heat, it will allow considerable heat to pass through it. Glass is diathermanous to luminous radiations, but only slightly so to obscure thermal radiations. A solution of alum is still less diathermanous to obscure thermal rays, although it allows the luminous rays to pass readily through it. A solution of iodine in bisulphide of carbon, on the contrary, is perfectly diathermanous to the obscure thermal rays, and perfectly opaque to the luminous rays. A polished plate of rock-

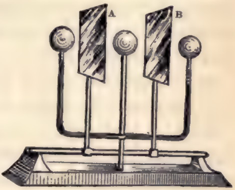
salt is diathermanous to both the obscure and luminous rays.

259. *The Effect of Rise of Temperature on Radiation.* — If the temperature of a body is gradually raised to the highest possible point, and a cell of the iodine solution is used to cut off the luminous radiations, the obscure thermal radiations will be found to grow more and more intense, both before and after the body begins to emit luminous radiations. A rise of temperature, then, has two effects upon the radiation of a body; it causes its obscure radiations to become more intense, and gives rise to new radiations. The latter radiations differ from the former in having quicker vibrations and shorter waves. The radiations of longest and shortest wave-lengths are obscure, while those of medium wave-lengths are luminous. The radiations of all wave-lengths are thermal, but the thermal power is greatest in radiations of long wave-lengths, and least in those of short wave-lengths. All radiations are capable of producing certain chemical effects, but this chemical or *actinic* power is least in radiations of long waves and greatest in the short waves. The radiations of bodies have, accordingly, been divided into three classes; namely, *obscure thermal*, *luminous*, and *obscure actinic*. At low temperatures bodies emit only the first class of radiations; at higher temperatures, the first and second classes; and at still higher temperatures, all three classes.

260. *Absorption.* — *Absorption* is the reverse of radiation. When the minute waves of the ether encounter the molecules of gross matter, they throw the atoms into vibration, provided these can vibrate at the same rate as the particles of the ether in the waves. In this way the rays are taken up and absorbed by bodies. It is only those rays which are absorbed by a body that heat it. Bodies are not warmed at all by the rays which they transmit.

261. *Good Radiators are Good Absorbers.* — Rough blackened surfaces are better radiators than smooth polished surfaces. This may be shown by the following experiment. Two metallic plates *A* and *B* (Figure 187) of the same size are mounted on standards which move to and fro on a sliding bar at the bottom. Between these plates there is a rod for supporting a ball at the height of the centre of the plates. *A* is coated with polished nickel on both sides, and *B* with nickel on one side and lampblack on the other. *B* is made to turn on its standard so that the surface coated with lampblack may be turned either towards the ball or from it. First, turn the nickel faces of the plate towards the ball, heat the ball to dull redness, place it upon its rod, and move both plates up against it so that they may be heated equally. Place a differential thermometer as shown in the figure, so that its bulbs shall be equally distant from the two plates. One of the bulbs will be heated by radiation from the nickel surface, and the other by radiation from the blackened surface. The liquid in the stem will move towards the former bulb, showing that the latter bulb is hotter, and that the radiation is more powerful from the blackened surface. Now reverse plate *B*, turning its blackened face towards the ball, remove the ball, and allow both plates to cool. Place each plate against one of the bulbs of the thermometer, and arrange them so that they shall be equally distant from the ball. Heat the ball and replace it on the rod. The plates will now become heated by absorption of radiations from the ball. They will receive equal radiations, but the thermometer will indicate that the plate with the lampblack coating towards

Fig. 187.



the ball is the hotter. Hence the blackened surface is the better absorber.

Different gases as well as different solids and liquids differ in their absorptive power and in the kind of rays which they absorb. Watery vapor among gases corresponds to glass among solids and a solution of alum among liquids. It is diathermanous to luminous rays, but much less so to obscure rays.

Stoves and radiators, which are designed to give out heat, should have rough blackened surfaces; while a teapot, which is designed to keep the liquid in it hot, should have a bright polished surface.

262. *Hot-Houses.* — A hot-house is a structure covered with glass. On a sunny day the temperature will be several degrees higher within such a structure than on the outside. The luminous heat which comes from the sun passes readily through the glass and falls upon the objects within. These absorb the heat and in turn send back obscure heat. This heat is stopped by the glass. Hence the heat accumulates within the hot-house. A hot-house may be described as a trap to catch sunbeams. Even at night and on a cold cloudy day it will be warmer within a hot-house than on the outside, the glass preventing the obscure radiations from passing off into space. The watery vapor in the atmosphere acts just like the glass of the hot-house.

IV.

LIGHT.

A. Radiation.

263. *Luminous Bodies.* — Bodies, like a gas-jet or the sun, which emit light of their own, are said to be *luminous.* Light is now believed to originate in extremely minute and rapid vibrations of the atoms of matter. These vary in rapidity from about 400 million million to about 760 million million a second. The atoms of all luminous bodies are supposed to be vibrating at this enormous rate.

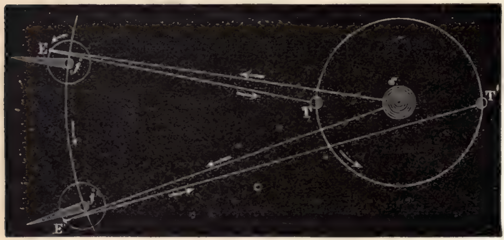
When a body is heated its atoms are thrown into more and more rapid vibrations, and when their rate of vibration reaches 400 million million a second the body begins to become luminous. In the case of a candle-flame or gas-jet, these rapid vibrations are produced by the clashing of the atoms of oxygen, hydrogen, and carbon as they rush into combination. A blacksmith may heat a nail red-hot by vigorously hammering it. Each blow of the hammer throws the atoms of the nail into more rapid vibration, till they finally vibrate fast enough to develop light.

264. *Propagation of Light by the Ether.* — As the atoms of matter vibrate in the ether in which they are immersed, they communicate their vibration to it. The vibrations thus started in the ether are propagated through it in every direction in minute waves and with an inconceivable velocity. These ethereal waves vary in length according to the rate of the atomic vibrations. It takes somewhat more than 35,000 of the longest of these waves, and somewhat

less than 70,000 of the shortest of them, to make the length of an inch. The vibrations are transverse, so that each luminous wave is made up of crest and hollow, like a water-wave. Light and luminous radiations are the same thing. The velocity of light is about 186,000 miles a second.

265. *Velocity of Light.* — The velocity of light was first determined by Roemer, a Danish astronomer, by a study of the eclipses of one of Jupiter's moons. He found by an examination of a long series of observations that the mean interval between two successive eclipses of the moon was about 42½ hours, but that the interval varied by a regular law, according to the motion of the earth with respect to Jupiter. When the earth was moving away

Fig. 188.



from Jupiter, from T to T' (Figure 188), the intervals were longer than the mean, till at T' the eclipse occurred about 16½ minutes late; and these intervals were longest when the earth was moving away from Jupiter most rapidly. When the earth was again moving towards Jupiter, from T' to T, the intervals were shorter than the mean, and shortest when the earth was moving most rapidly towards Jupiter. Now we cannot be aware of the eclipse till the light which left the moon just as it entered Jupiter's shadow has reached the earth; and the distance this light has to

travel is continually increasing as the earth travels from T to T', and decreasing as the earth travels from T' to T. Roemer concluded that this must be the reason why the intervals between the eclipses were longer than the mean in the one case and shorter in the other. As the eclipse occurred 16½ minutes late at T', he concluded that it must take light about 16½ minutes to cross the earth's orbit. As this distance is about 184,000,000 miles, light must travel at the rate of about 186,000 miles a second. This velocity would carry light around the earth in about ⅛ of a second. Great as is this velocity, it is believed that the nearest fixed star is so distant that it would take light over three years to reach us from it, while the most distant stars are at least a thousand times more remote.

Were all the stars in the heavens to be blotted out of existence to-night, it would be over three years before we should miss any of them, a quarter of a century before we should miss many, and thousands of years before we should lose them all. The light which will enter our eyes as we glance at some star to-night probably started on its journey before the building of the great pyramids, and has been travelling 8 times the distance around the earth every second since.

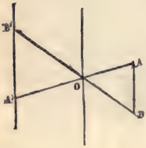
266. *Rectilinear Propagation of Light.* — When sunlight enters through an opening into a darkened room, it illumines the dust in the atmosphere in its path, which may then be easily traced. This path is always found to be straight. Light always traverses a homogeneous medium in straight lines. A single line of light is called a *ray*, and a collection of rays a *beam*.

267. *Images produced by Small Apertures.* — If a white screen is placed opposite a small opening in a shutter of a darkened room, an inverted picture of the outside landscape will be formed on the screen, all the movements and colors being correctly represented (Figure 189). The smaller the opening, the sharper the image.

Fig. 189.

The formation of this image is due to the rectilinear propagation of light, and may be explained by means of Figure 190. The point A is sending out rays in all directions in straight lines. The rays from this point which pass through the small opening must fall upon A' of the screen. In the same way, the rays from B which pass through the opening must fall upon B'. As A sends light to no part of the screen except A', and as A' receives light from no part of the object but A, the color and brightness of the spot A' will depend upon the color and brightness of A; in other words, A' will be the image of A. In like manner B' will be the image of B, while the points of the object between A and B will have their images at corresponding points between A' and B'. An inverted image of A B will thus be formed between A' and B'.

Fig. 190.



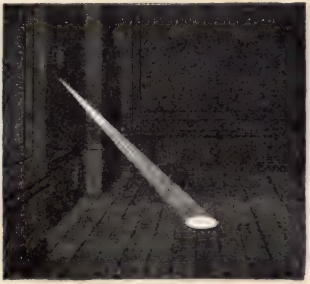
When the opening is large, the rays passing through each point of it will form an image on the screen. These

images will fall upon one another, but will not exactly coincide. Hence, as the opening is enlarged, the image becomes blurred, until finally it is entirely obliterated.

Fig. 191.

A similar experiment to the above may be tried by holding a card with a large pin-hole in it between a candle and a screen, as shown in Figure 191. An inverted image of the candle will be formed on the screen.

Fig. 192.



When the sun shines through a small hole into a room

with the blinds closed, no matter what may be the shape of the opening, the image of the sun formed on the floor or wall will be round or oval, according as it falls upon a surface which is perpendicular or oblique to the rays (Figure 192).

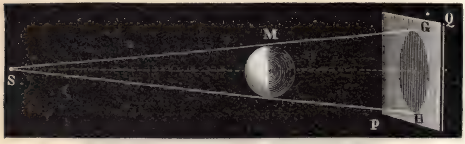
When the sun shines through the foliage of trees, the spots of light on the ground will always be round or oval, whatever may be the shape of the openings through which the sun shines, provided they are sufficiently small.

When the sun is undergoing eclipse, the progress of the eclipse may be watched by noticing the shape of these spots, which will always be that of the uneclipsed portion of the sun's disc.

268. *Shadows.* — Bodies which, like glass, will allow light to pass readily through them, are said to be *transparent.* Bodies which will not allow light to pass through them are said to be *opaque.*

Owing to the rectilinear propagation of light, opaque bodies in front of a light must necessarily shut off the light from some of the space behind them. In doing this they are said to cast *shadows.*

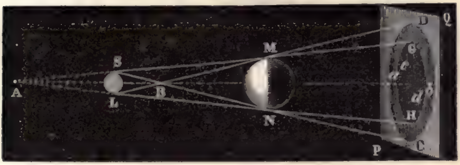
Fig. 193.



If the luminous body S (Figure 193) is a mere point, the body M will cast a well-defined shadow GH upon the screen PQ. If the straight line SG is kept fast at S, and carried round the sphere M, touching it all the time, it will describe a *cone.* The part MG, as it passes round, will exactly mark the limits of the shadow cast by M. Whether the shadow received on the screen is round or oval will depend upon whether the screen is perpen-

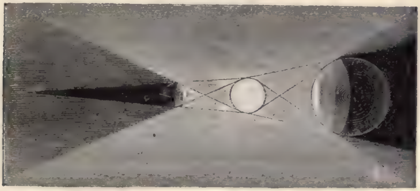
dicular or oblique to the axis of the shadow. If the luminous body is not a mere point, the shadow of *M* (Figure 194) upon the screen will be indistinct in outline.

Fig. 194.



Prolong the line *G S* to *A*. Keep the point *A* fixed and carry the line *A G* around the spheres *S* and *M*, keeping it all the while in contact with both. The line will describe a cone which will touch the two spheres *externally*, and the part *M G* will mark out the space from which the light is entirely excluded. This portion is called the *umbra* of the shadow. If the line *S C* is kept fixed at *B*, and then carried round the two spheres so as to be kept in contact with both of them, all the time, it will describe a *double* cone, whose apex will be at *B* and which will touch the two spheres *internally*. The part *N C* of this line will mark the extreme limits of the shadow. From the portion of the shadow outside of the umbra only a portion of the

Fig. 195.



light is excluded, and the farther we pass from the umbra the less the light excluded. This portion of the shadow is called the *penumbra*. It will be seen at once from the figure, that

the light from S will reach all the space between D and G, and the light from L all the space between C and H.

Suppose a luminous body (Figure 195) placed between two opaque bodies, one of them larger and the other smaller than itself. Conceive a cone touching the luminous body and either of the opaque bodies *externally*. This will be the cone of *total shadow*, or the cone of the *umbra*. All points within it are completely excluded from view of the luminous body. This cone narrows or enlarges as it recedes, according as the opaque body is smaller or larger than the luminous body. In the former case, it terminates at a finite distance; in the latter, it extends to an infinite distance. Now conceive a double cone touching the luminous body and either of the opaque bodies *internally*. This cone will be wider than the cone of total shadow, and will include it. It is called the cone of *partial shadow*, or the cone of the *penumbra*. All points lying within it are excluded from the view of some portion of the luminous body. If they are nearer its outer boundary, they are very slightly shaded. If they are so far within it as to be near the total shadow, they are almost completely shaded. If, therefore, the shadow of the opaque body is received on a screen, it will not have sharply defined edges, but will show a gradual transition from the total shadow of the central portion to a complete absence of shadow at the outer boundary of the penumbra. Thus neither the edges of the umbra nor those of the penumbra are sharply defined.

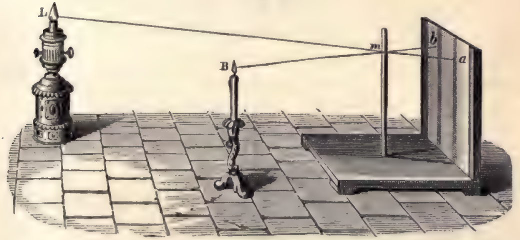
Fig. 196.

269. *Illumination.*—The illuminating power of a source of light diminishes as the square of the distance from the illuminating body increases. In Figure 196 the disc $C D$ is held parallel with the screen $A B$, and half-way between

the screen and the source of light L. The diameter of the shadow on the screen will be twice that of the disc, and the area of the shadow four times that of the disc. The disc receives all the light that would fall upon the space covered by the shadow, were the disc removed. Hence the illumination of the disc is four times as intense as that of the screen. If the disc were held one third of the way from L to the screen, the area of the disc would be one ninth that of its shadow on the screen, and the illumination of the disc would be nine times as intense as that of the screen.

270. *Photometry.* — *Photometry* is the measurement of the relative illuminating power of different sources of light. An instrument used for this measurement is called a *photometer*. Rumford's photometer is one of the simplest of these instruments. Its use is based upon the comparison of shadows. An opaque rod M (Figure 197) is placed in

Fig. 197.



front of a ground-glass screen. The lights L and B to be compared are placed so that each casts a separate shadow of the rod upon the screen. These distances are then made such that the two shadows a and b are of exactly the same intensity. The screen must then be receiving the same illumination from each light; for the shadow cast by B is illumined by L, and that cast by L is illumined by B. Hence the illuminating power of the two lights

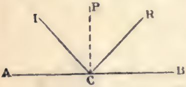
will be to each other as the squares of the distances of the lights from the screen.

B. Reflection.

271. *Diffusion.* — When light meets the surface of a new medium, a portion of it is thrown back and scattered irregularly in every direction. This light is said to be *diffused.* It is by means of the light thus diffused that we are enabled to see the surfaces of non-luminous bodies. Smooth polished surfaces diffuse less light than rough irregular ones, but the most highly polished mirror diffuses enough light to enable us to see its surface, though sometimes with difficulty.

272. *Reflection.* — On meeting the surface of a new medium, a portion of the light is thrown back in a definite direction. This light is said to be *reflected.* In Figure 198, $A\,B$ represents the surface of the new medium, $I\,C$ the ray coming to the medium, or the *incident* ray, and $C\,R$ the *reflected* ray. $P\,C$ is a perpendicular to the surface of the medium at the point C. The angle $I\,C\,P$ is called the *angle of incidence*, and the angle $R\,C\,P$ is called the *angle of reflection.*

Fig. 198.



In reflection, the angles of incidence and reflection are always equal to each other. The smoother the surface of a medium, the greater the proportion of the light reflected from it. Good reflecting surfaces are called *mirrors.*

273. *Images formed by Plane Mirrors.* — It is by reflected light that we see objects mirrored in reflecting surfaces. The reflecting surface is said to form *images* of the object. These visible images of objects formed by reflection correspond to the echoes formed by reflection in the case of sound.

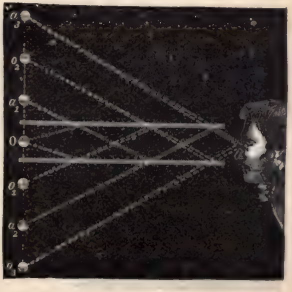
Figure 199 represents a pencil of rays emitted from the

highest point of a candle-flame to the eye of an observer. The rays have exactly the same degree of divergence after reflection as before, and if prolonged backward would meet just as far behind the mirror as the point from which they come is in front of it. The same would be true of the rays coming from every point of the object. Hence an image seen in a plane mirror will seem just as far behind the mirror as the object is in front of it. This is not only true of the image as a whole, but also of each part of the image. If the object is parallel with the surface of the mirror, the image will appear parallel with the surface of the mirror; if the object is at any angle to the surface of the mirror, the image will appear at the same angle to the surface of the mirror on the other side, each point of the image appearing just as far behind the mirror as the corresponding point of the object is in front of it.

Fig. 199.

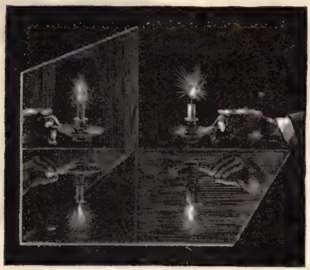
274. *Multiple Images formed by two Parallel Plane Mirrors.* — When an object O is placed between two parallel plane mirrors (Figure 200), the rays of light from it may reach the eye after one, two, or three reflections. The rays which reach the eye after one reflection from the upper mirror would form the image a_1, and those that reach the eye after one reflection from

Fig. 200.



the lower mirror would form the image o_1. The rays which reach the eye after two reflections, one from each mirror, would form the images o_2 and a_2; and those which reach the eye after three reflections, the images a_3 and o_3. In the figure, only those rays are represented which reach the eye after three reflections.

Fig. 201.



275. *Images formed by two Mirrors at an Angle to each other.* — Figure 201 shows the images that would be formed by two mirrors at right angles to each other, one being horizontal and the other vertical.

Figure 202 shows the images that would be formed if an object were placed between two mirrors facing each other at an angle of 60°. When the mirrors are inclined to each other, the images that are formed by multiple reflections are always arranged in the circumference of a circle, whose centre is at the intersection of the two mirrors, and whose circumference passes through the object.

Fig. 202.

276. *The Kaleidoscope.* — The

kaleidoscope is an optical toy, invented by Sir David Brewster. It consists of a tube containing two glass plates, extending along its whole length, and inclined at an angle of 60°. One end of the tube is closed by a metal plate, with the exception of a hole in the centre, through which the observer looks in ; at the other end there are two plates, one of ground and the other of clear glass (the latter being next the eye), with a number of little pieces of colored glass lying loosely between them. These colored objects, together with their images in the mirrors, form symmetrical patterns of great beauty, which can be varied by turning or shaking the tube, so as to cause the pieces of glass to change their positions (Figure 203).

Fig. 203.

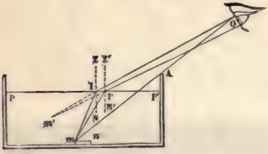
A third reflecting plate is sometimes employed, the cross-section of the three forming an equilateral triangle. As each pair of plates produces a kaleidoscopic pattern, the arrangement is nearly equivalent to a combination of three kaleidoscopes.

The kaleidoscope is capable of rendering important aid to designers.

C. Refraction.

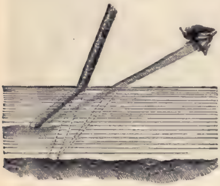
277. *Illustration of Refraction.* — If a beam of light is allowed to fall obliquely upon water, it will be seen to be bent on entering the water, though it will continue to move on in a straight line after it has passed into the water. This bending of a ray of light, on passing obliquely from one medium to another, is called *refraction.*

Fig. 204.



If a coin or other object $m\,n$ (Figure 204) is placed on the bottom of a vessel with opaque sides, so as just to be concealed from an eye at O, and the vessel is then filled with water, the bottom of the vessel will seem to rise and the object will come into view. This is because the pencils of rays coming from the object at m will be suddenly bent on entering the air, and will reach the eye as if they came from m', where the object will appear to be.

Fig. 205.



For a similar reason, a stick partly immersed in water, in an oblique position, will appear bent, as shown in Figure 205.

278. *Two Cases of Refraction.* — When a ray of light passes obliquely from a rarer into a denser medium, it is bent towards a perpendicular drawn to the surface of the medium at the point of contact of the ray. In Figure 206, $A\,B$ represents the surface of a denser medium, $I\,C$ the incident ray, $C\,R$ the refracted ray, and $P\,C\,H$ a perpendicular to the surface of the medium at the point C. The

Fig. 206.

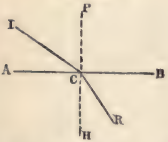
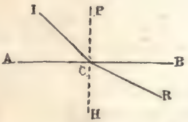


Fig. 207.



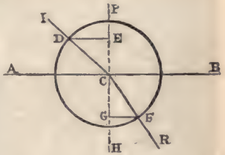
angle $R\,C\,H$ is the *angle of refraction.* In this case the angle of refraction is *less* than the angle of incidence.

When a ray of light enters a rarer medium obliquely, it is bent from a perpendicular to the surface of the medium at the point of contact. In Figure 207, *A B* represents the surface of a rarer medium, *I C* the incident ray, *C R* the refracted ray, and *P C H* the perpendicular. In this case the angle of refraction is *greater* than the angle of incidence.

When a ray of light enters any medium perpendicularly, there is no refraction.

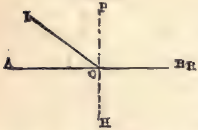
279. *Law of Refraction.* — In Figure 208, *A B* represents the surface of a denser medium, *I C* the incident ray, *C R* the refracted ray, *P C H* the perpendicular to the surface of the medium at the point of the contact of the ray. A circle of any radius is described about the point *C* as a centre, and from the points *D* and *F* where this circle cuts the incident and refracted rays, the lines *D E* and *F G* are drawn at right angles to the perpendicular *P C H*. These lines are called the *sines* of the angles *I C P* and *R C H*, respectively. The law of refraction is this: If the size of the angle of incidence is changed, the size of the angle of refraction will change in such a way that the length of the lines *D E* and *F G* will change at the same rate. As one increases in length, the other increases in length and at the same rate, and *vice versa*. This law is usually stated as follows: *For the same media the sines of the angles of incidence and of refraction always bear the same ratio.* This ratio is called the *index of refraction* for the *media*. When light is passing from air to glass the sines of these angles are as 3 to 2; and from air to water, as 4 to 3. The index of refraction for the former media is $\frac{3}{2}$ and for the latter $\frac{4}{3}$.

Fig. 208.



280. *Total Reflection.* — The angle of incidence may have any value from 0° up to 90°. When light enters a denser medium, the angle of refraction is less than the angle of incidence, and hence always less than 90°. But

Fig. 209.



when light enters a rarer medium, there is always a certain angle of incidence ICP (Figure 209) at which the angle of refraction HCR is equal to 90°. This angle is called the *limiting angle*, or the *critical angle*. When the media are air and water, this angle is about 48½ degrees. For air and the different kinds of glass it ranges from 38° to 41°.

When the angle of incidence exceeds the limiting angle,

Fig. 210.

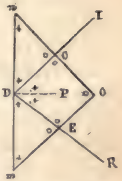
none of the light will enter the medium, however transparent it may be. In this case the light will be *totally reflected*, the angle of reflection being equal to that of incidence.

If a glass of water, with a spoon in it, is held above the level of the eye (Figure 210), the under side of the surface of the water is seen to shine like polished silver, and the lower part of the spoon is seen reflected in it. The rays of light which pass upward through the water at a certain angle are totally reflected on meeting the air.

281. *Path of a Ray through a Rectangular Prism of Glass.* — By a *rectangular* prism in optics is meant a prism whose base is an isosceles right-angled triangle.

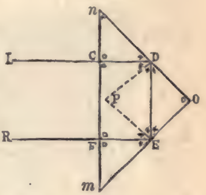
Suppose a ray of light $I\,C$ (Figure 211) to meet one of the narrower sides $n\,o$ of the rectangular prism $m\,n\,o$ perpendicularly. At D it will be totally reflected, since it will meet the air at the angle of incidence $C\,D\,P$ equal to $45°$. At E it will pass out of the prism without bending because it will meet the surface perpendicularly. This ray will be totally reflected once and turned $90°$ out of its original course. All the angles in the figure marked with a small circle are right angles, and those marked with a cross are angles of $45°$.

Fig. 211.



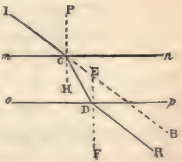
Suppose the incident ray $I\,C$ (Figure 212) to meet the broader side $m\,n$ of the prism perpendicularly. It will enter without bending since it meets the surface perpendicularly. At D it will be totally reflected, since it meets the air at an angle of $45°$. At E it will again be totally reflected, since it again meets the air at an angle of $45°$. At F it will leave the prism without bending, since it meets the surface perpendicularly. In this case the ray is totally reflected twice, and turned $180°$ from its original course. The angles in this figure are marked as before. By means of a total-reflecting prism, the direction of rays of light may be changed without loss of light.

Fig. 212.



282. *Path of a Ray through a Dense Medium with Parallel Sides.* — In Figure 213, $m\,n$ and $o\,p$ represent the parallel sides of some dense medium, as glass. $I\,C$ represents the ray coming to the first surface, and $C\,B$ is the prolongation of the direction of the incident ray. On entering the medium, the ray is bent towards the perpendicular $P\,C\,H$, and on leaving the medium at D, it is bent from the

Fig. 213.

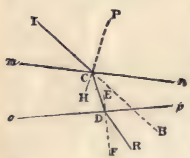


perpendicular $E D F$. The second bending is equal to the first and in the opposite direction, so that the ray $D R$ emerges from the medium with the same direction it had before entering the medium. Had the ray started from R and met the medium at D, it would have taken the same path back through the medium, and have emerged with the direction $C I$. This is only one case of the general law that the course of the returning ray is the same as that of the direct ray.

283. *Path of a Ray through a Dense Medium with Inclined Sides.* — Whenever a ray of light traverses a denser medium with inclined sides, it will be turned aside towards the thicker part of the medium.

In Figure 214, the ray $I C D R$ is represented as passing through the medium in such a way as to be bent twice, once at C towards the thicker part of the medium, and once at D towards the thinner part. In every such case the bending towards the thicker part of the medium will be greater than that towards the thinner part. Hence the resultant deviation of the ray from its original course will be towards the thicker part of the medium.

Fig. 214.



In Figure 215, the ray is represented as passing through

Fig. 215.

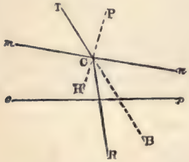
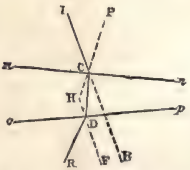


Fig. 216.



the medium in such a way as to be bent only once, since it meets one side of the medium perpendicularly. In this

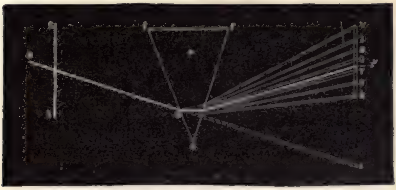
case the bending will be always towards the thicker part of the medium.

In Figure 216 the ray is represented as passing through the medium in such a way as to be bent twice, both times towards the thicker part of the medium. In all three cases the path of the ray would be the same, whether the ray starts from *I* or *R*.

D. Dispersion.

284. *The Dispersion Spectrum.* — If a glass prism is held with its edge down in the path of a thin beam of light, the spot of light on the screen will be raised and be

Fig. 217.



changed into a beautifully colored band, in which the colors are arranged in the order of *red*, *orange*, *yellow*, *green*, *blue*, *indigo*, and *violet*. The colored band produced by the passage of a beam of light through a prism is called the *dispersion spectrum*. The raising of the spot of light on the screen is due to the bending of the beam as a whole towards the thicker part of the medium; and the formation of the colored band, to the unequal bending of the different colored rays of which white light is composed, red being bent the least and violet the most of all the rays. The separation of the colored rays by refraction is called *dispersion*. The action of the prism on the rays is shown in Figure 217.

The *refrangibility* of light is found to depend upon the length of its waves; the shorter the waves, the more refrangible the ray. The violet rays are more refrangible than the red because they have shorter waves.

In the case of sunlight and of light from any intense source of heat, it is found that the thermal power of the spectrum extends considerably beyond the red, and the chemical power considerably beyond the violet. The complete spectrum is composed of three parts, a *luminous* portion at the centre, an *obscure thermal* portion beyond the red, and an *obscure actinic* portion beyond the violet. Every portion of the spectrum is *thermal*, but the thermal power increases rapidly as we approach the red end, and is greatest in the region just beyond the red. Every part of the spectrum is also *actinic*, but the greatest actinic power is in the region of the blue. Only the central part of the spectrum is *luminous*, and the greatest luminosity is in the region of the yellow and green.

285. *Achromatic and Direct-Vision Prisms.*—The refractive power of a substance is independent of its dispersive power. Hence, by using different kinds of glass, it has been found possible to construct prisms which shall have equal refractive and unequal dispersive powers, or equal dispersive and unequal refractive powers. If two prisms of crown and flint glass are constructed so as to have equal powers of bending a beam of light as a whole, the flint-glass prism will produce greater dispersion than the crown-glass. If, on the other hand, the two prisms are constructed so as to produce equal dispersion, the crown-glass prism will bend the ray as a whole more than the flint-glass.

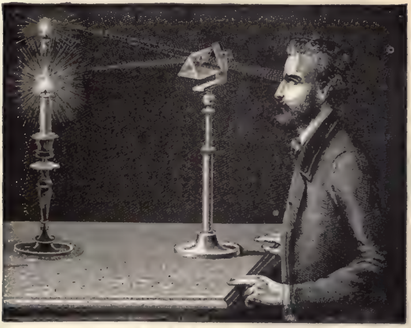
The refractive and dispersive powers of a prism both increase with the inclination of its sides. When two prisms of equal dispersive and unequal refractive powers are combined, with the thicker part of one beside the thinner part of the other (Figure 218), they form what is called an

achromatic prism. Such a prism will produce refraction without dispersion. *Achromatic* means *without color.*

When two prisms of equal refractive powers and unequal dispersive powers are combined as above, they form what is called a *direct-vision prism.* Such a prism produces dispersion without refraction. It takes its name from the fact that in using it you look directly at the object you wish to examine, while, with any other prism, you are obliged to look somewhat away from the object, as is shown in Figure 219.

Fig. 218.

Fig. 219.



286. *The Spectroscope.* — The *spectroscope* is an instrument for examining spectra. A *simple* spectroscope is shown in Figure 220. The tube at the right is called the *collimator* tube. The light to be examined is admitted through a narrow opening at the end of the tube, and the rays are rendered parallel by means of a lens within it. The light is then dispersed by the prism, and the spectrum examined

by means of the telescope at the left of the prism. The tube in front of the prism has a scale engraved on glass in

Fig. 220.

the opening at the end next to the candle. The light from the candle which shines through this scale is reflected from the side of the prism into the telescope, so as to form an image of the scale alongside that of the spectrum. The power of the spectroscope may be increased by using a train of prisms to disperse the light instead of a single prism. The arrangement of the prisms is shown in Figure 221. The end of the collimator tube is seen at the left, and that of the telescope at the right.

Fig. 221.

A *direct-vision* spectroscope is one in which direct-vision prisms are used.

287. *Three Kinds of Spectra.* — If we examine with the

spectroscope the light from an incandescent solid, its spectrum will be found to be a continuous band of colors, changing by insensible gradations from red at one end to violet at the other. Such a spectrum is called a *continuous* spectrum. Incandescent solids and liquids give continuous spectra.

If we examine with the spectroscope the light from luminous strontium vapor, its spectrum (see frontispiece) will be seen to be made up of bright lines and dark spaces. Such a spectrum is called a *bright-lined* or *broken* spectrum. Vapors and gases, when luminous, give bright-lined spectra. The spectra of different gases and vapors differ in the number and position of these lines. Hence a vapor may be recognized by its spectrum.

The dark spaces of these spectra are due to the absence of certain rays. While incandescent solids and liquids emit rays of all degrees of refrangibility, luminous vapors and gases emit those only of particular degrees of refrangibility. Each vapor or gas emits just as many sets of rays as there are bright lines in its spectrum. The number of these lines ranges from one up to several hundred. The lines of the spectrum of a vapor change somewhat with the temperature of the vapor. The analysis of light by means of the spectroscope is called *spectrum analysis*.

The spectrum of an incandescent solid or liquid, when shining through a luminous vapor or gas, is made up of *dark lines* separated by bright spaces, there being a dark line for every bright line which the gas alone would give. Such spectra are called *reversed spectra*, the spectrum of the gas being reversed by the light of the solid which passes through it.

288. *Explanation of Reversed Spectra.* — It has been found that gases absorb and quench rays of the same degree of refrangibility as those which they themselves emit, and no others. When a solid is shining through a luminous vapor, this absorbs and

quenches those rays from the solid which have the same degrees of refrangibility as those which it is itself emitting. Hence the lines of the spectrum receive light from the vapor alone, while the spaces between the lines receive light from the solid. Now solids and liquids when heated to incandescence give a very much brighter light than vapors and gases at the same temperature. Hence the lines of a reversed spectrum, though receiving light from the vapor or gas, appear dark by contrast.

289. *The Molecular Theory of Radiation.* — The following account of the molecular theory of radiation is taken from Maxwell's "Molecular Theory of Heat:" —

"If the parts of the molecule are capable of relative motion without being altogether torn asunder, this relative motion will be some kind of vibration. The small vibrations of a connected system may be resolved into a number of simple vibrations, the law of each of which is similar to that of a pendulum. It is probable that in gases the molecules may execute many of such vibrations in the interval between successive encounters. At each encounter the whole molecule is roughly shaken. During its free path it vibrates according to its own laws, the amplitudes of the different simple vibrations being determined by the nature of the collision, but their periods depending only on the constitution of the molecule itself. If the molecule is capable of communicating these vibrations to the medium in which radiations are propagated, it will send forth radiations of certain definite kinds, and if these belong to the luminous part of the spectrum, they will be visible as light of definite refrangibility. This, then, is the explanation, on the molecular theory, of the bright lines observed in the spectra of incandescent gases. They represent the disturbance communicated to the luminiferous medium by molecules vibrating in a regular and periodic manner during their free paths. If the free path is long, the molecule, by communicating its vibrations to the ether, will cease to vibrate till it encounters some other molecule.

"By raising the temperature we increase the velocity of the motion of agitation and the force of each encounter. The higher the temperature the greater will be the amplitude of the internal vibrations of all kinds, and the more likelihood will there be that vibrations of short period will be excited, as well as those funda-

mental vibrations which are most easily produced. By increasing the density we diminish the length of the free path of each molecule, and thus allow less time for the vibrations excited at each encounter to subside; and since each fresh encounter disturbs the regularity of the series of vibrations, the radiations will no longer be capable of complete resolution into a series of vibrations of regular periods, but will be analyzed into a spectrum showing the bright bands due to the regular vibrations, along with a ground of diffused light, forming a continuous spectrum due to the irregular motion introduced at each encounter.

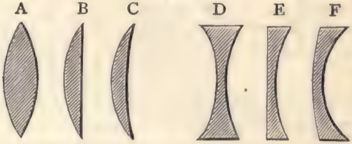
"Hence, when a gas is rare, the bright lines of its spectrum are narrow and distinct, and the spaces between them are dark. As the density of the gas increases, the bright lines become broader, and the spaces between them more luminous.

"When the gas is so far condensed that it assumes the liquid or solid form, then, as the molecules have no free path, they have no regular vibrations, and no bright lines are commonly observed."

E. Lenses.

290. *Forms of Lenses.* — A *lens* is a transparent medium having at least one curved side. Lenses are usually

Fig. 222.



made of glass, and are circular in outline. Their curved surfaces are usually spherical. They are divided into two classes, according to their shape, namely, *convex lenses* and *concave lenses*. Every convex lens has at least one *convex* surface, and is thickest at the centre; and every concave lens has at least one *concave* surface, and is thickest at the

margin. There are three forms of each class of lenses. These six forms of lenses are shown in section in Figure 222. The first three are convex and the last three concave lenses. *A* is a *double-convex* lens, having two convex surfaces. *B* is a *plano-convex* lens, having one plane and one convex surface. *C* is a *concavo-convex* lens, having a concave and a convex surface, the convex surface having the greater curvature. This lens is often called a *meniscus*. *D* is a *double-concave* lens, having two concave surfaces. *E* is a *plano-concave* lens, having a plane and a concave surface. *F* is a *convexo-concave* lens, having a convex and a concave surface, the concave surface having the greater curvature.

291. *Optical Centre of Lenses.* — There is for every lens a certain point, any straight line drawn through which will meet on opposite sides of the lens portions of surface which are parallel to each other. The point is called the *optical centre* of the lens.

The optical centre of any lens with two curved surfaces may be found by the following construction. In Figure 223, *A* and *B* are the centres of the two surfaces of the lens *m p o* and *m n o*. From *A* draw any radius *A C*, and from *B* draw the radius *B D* parallel to *A C*. Join the points *A* and *B*, and *C* and *D* with straight lines. The point *O* where these lines cross will be the optical centre of the lens. The portions of surface at *C* and *D* will be parallel to each other, since each will be perpendicular to the radius drawn to that point, and these radii are parallel to each other. If any straight line whatever were drawn through *O*, the points of surface where this line intersects the sides of the lens would be parallel to each other.

Fig. 223.

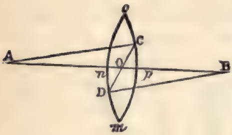


Fig. 224.

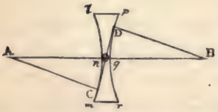


Figure 224 shows the same method applied to a double-concave lens. In the case of a double-convex and a double-concave lens the optical centre is within the lens.

Fig. 225.

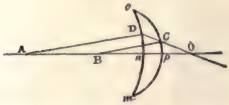
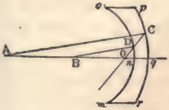


Fig. 226.



Figures 225 and 226 show the above method applied to a concavo-convex lens and to a convexo-concave lens. In these cases the optical centre is without the lens on the side of the greater curvature.

The optical centre of a *plane* lens is at the middle point of

Fig. 227.

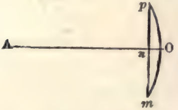
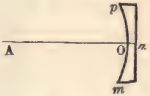


Fig. 228.



its curved surface. This is evident from Figures 227 and 228. The radius $A\ O$ drawn to the middle point of the curved surface $m\ O\ p$ will be perpendicular to the plane side at the point n, and to the curved surface at O, for a radius drawn to the middle point of an arc is perpendicular to the chord of the arc, or to a line parallel with it Hence the point of the surface at O is parallel to every portion of the plane side. Therefore any straight line drawn through O would meet on opposite sides of the lens portions of surface parallel to each other.

292. *Axes and Foci of Lenses.* — Any straight line drawn through the optical centre of a lens is called an *axis.* An axis which passes through the centre of curvature of a lens is called the *principal* axis, and every other axis a *secondary* axis. Every ray of light which coincides with an axis will emerge from a lens with the same direction it had before entering, since it will pass through a portion of

a medium having parallel sides. Every other ray which passes through a lens will be deflected towards the thicker part of the lens, since it will pass through a portion of a medium having inclined sides. In the case of a convex lens the deflection will be towards the *centre* of the lens, and of a concave lens towards the *margin*.

When the rays, on emerging from a lens, are either convergent or divergent, the points towards which they converge or from which they diverge are called *foci*. When the rays are convergent on emerging from the lens, the focus is *real;* and when they are divergent, *virtual*.

Fig. 229.

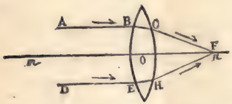
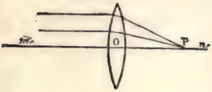


Fig. 230.



293. *Parallel Rays with Lenses.* — Figure 229 represents the case of parallel rays with a convex lens when the rays are parallel to the principal axis and lie on opposite sides of it. The lens being thickest at the centre, the rays are deflected towards the axis, and so become convergent and meet at the point F.

Figure 230 shows the case of parallel rays with a convex lens when the rays are parallel with the principal axis and are on the same side of it. The rays are both deflected towards the axis and made convergent, because the marginal ray is deflected more than the central one, the inclination of the sides of the lens becoming greater and greater as we pass from the centre of the lens to the margin.

Fig. 231.

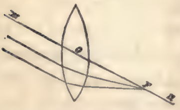


Figure 231 shows the case of parallel rays with a convex lens when the rays are parallel with a secondary axis and lie on the same side of it.

Parallel rays with a convex lens become convergent on emerging from the lens, and have a real focus, on the opposite side of

the lens to that on which they enter, and on the axis to which the rays are parallel.

Fig. 232.

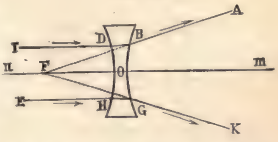


Figure 232 represents the case of parallel rays with a concave lens when the rays are parallel with the principal axis and lie on opposite sides of it. The rays are deflected from the axis, because the lens is thickest at the margin, and so become divergent, with *F* as their point of divergence.

Fig. 233.

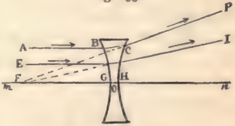


Figure 233 represents the case of parallel rays with a concave lens when the rays are parallel with the principal axis and lie on the same side of it. The rays are deflected from the axis, and the marginal ray is deflected more than the central one, because of the greater inclination of the sides towards the margin; and because of the greater deflection of the marginal ray the rays become divergent, with their point of divergence at *F*.

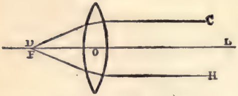
Parallel rays with a concave lens become divergent, and have a virtual focus on the same side of the lens as that on which the rays enter and on the axis to which the rays are parallel.

294. *Principal Foci and Focal Length.* — The focus for parallel rays is called the *principal focus* of the lens. It may be real or virtual, and on the principal axis or on a secondary axis. The distance from the optical centre of a lens to the principal focus is called the *focal length* of the lens. The greater the curvature of a lens, and the greater the refractive power of the material of which it is composed, the shorter the focal length of the lens.

295. *Divergent Rays with Lenses.* — (1.) Figure 234 represents the case of divergent rays with a convex lens when the

point of divergence is on the principal axis of the lens and at the focal length of the lens. This is the reverse of the case shown in Figure 229. Hence, according to the principle of the reversibility of the paths of rays of light through a medium, the rays would become parallel on emerging from the lens. In the case of rays diverging from the focal length of a convex lens, the rays always become parallel to the axis on which the point of divergence lies.

Fig. 234.



(2.) Figures 235 and 236 represent the case of divergent rays with a convex lens when the point of divergence is beyond the focal length. In Figure 235 the point of divergence is on the

Fig. 235.

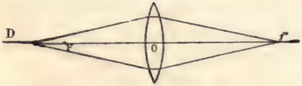
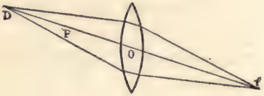


Fig. 236.



principal axis, and in Figure 235 on a secondary axis. Since the rays, on meeting the lens, are less divergent than in the preceding case, they become convergent on emerging from the lens, and have a real focus at *f*.

The nearer the point *D* to *F*, the more nearly parallel the rays emerging from the lens, and the farther the focus from the lens.

Divergent rays with a convex lens, the point of divergence being beyond the focal length of the lens, become convergent on emerging from the lens, and have a real focus on the opposite side of the lens to that on which the rays enter, on the same axis as the point of divergence, and

at a distance greater than the focal length, and increasing with the nearness of the point of divergence to the principal focus of the lens.

(3.) Figures 237 and 238 represent the case of divergent rays with a convex lens when the point of divergence is within

Fig. 237.

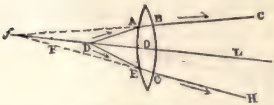
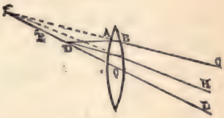


Fig. 238.



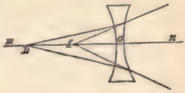
the focal length of the lens. The rays are more divergent on meeting the lens than in the first case. Hence they become only *less* divergent on emerging from the lens, and have a virtual focus at *f*.

The nearer the point *D* to *F*, the more nearly parallel the rays on emerging from the lens, and the more distant the focus *f*.

Divergent rays with a convex lens, when the point of divergence is within the focal length of the lens, become less divergent on emerging from the lens, and have a virtual focus on the same side of the lens as that on which the rays enter, on the same axis as the point of divergence, and at a distance from the lens greater than that of the point of divergence, and increasing with the nearness of the point of divergence to the principal focus.

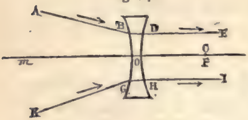
(4.) Figure 239 represents the case of divergent rays with a concave lens. The rays become more divergent, and have a virtual focus, on the same side of the lens as that on which the rays enter, on the same axis as the point of divergence, and nearer the lens.

Fig. 239.



296. *Convergent Rays with Lenses.* — (1.) Figure 240 represents the case of convergent rays with a concave lens, with the point of convergence (*C*) at the focal length. This is the

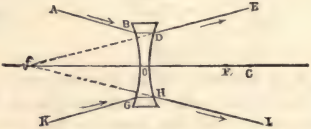
Fig. 240.



reverse of the case represented in Figure 232. The rays, on emerging from the lens, become parallel with the axis on which the point of convergence lies.

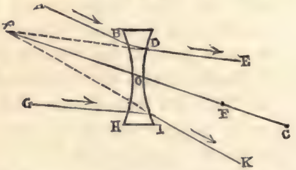
(2.) Figures 241 and 242 represent the case of convergent rays with a concave lens when the point of con-

Fig. 241.



vergence is beyond the focal length of the lens. The rays, being less convergent on meeting the lens than in the previous case, become divergent on emerging from the

Fig. 242.

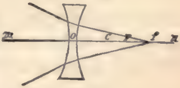


lens, have a virtual focus on the same side of the lens as that on which the rays enter, on the same axis as the point of convergence, and farther from the lens than the focal length of the lens. The nearer the point of convergence to the principal focus of the lens, the more distant the focus of the rays, because the more nearly parallel the rays on emerging from the lens.

(3.) Figure 243 represents the case of convergent rays with a concave lens when the point of convergence is within the focal

length of the lens. The rays are more convergent on meeting the lens than in the first case. Hence they become only *less* convergent on emerging from the lens, and have a real focus, on the opposite side of the lens to that on which they enter, on the same axis as the point of convergence, and at a distance from the lens greater than that of the point of convergence.

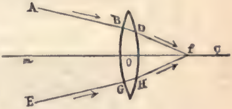
Fig. 243.



The nearer the point of convergence to the principal focus of a lens, the more distant the focus, because the more nearly parallel the rays on emerging from the lens.

(4.) Figure 244 represents the case of convergent rays with a convex lens. The rays become more convergent on emerging from the lens, and have a real focus, on the opposite side of the lens to that on which the rays enter, on the same axis as the point of convergence, and nearer than the point of convergence to the lens.

Fig. 244.



297. *Images formed by Lenses.* — Rays are diverging from every point on the surface of an object; that is to say, every point on the surface of an object is a point of divergence. The focus of a point is a copy or *image* of that point, and the foci of all the points on the surface of an object form an image of the object.

To find the image of an object, it is necessary to find only the foci of its extremities. To find these foci, we have only to draw axes through the extremities of the object, and locate the foci on these axes, according to the case of divergent rays under which they come.

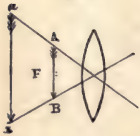
(1.) Figure 245 represents the case of an object $A\,B$ beyond the focal length of the lens. The image $a\,b$ is real, because made up of real foci; inverted,

Fig. 245.

because the axes cross between the image and the object; and in this case larger than the object, because farther than the object from the lens. Were the object distant, the image would be nearer than the object to the lens, and consequently smaller than the object. The nearer the object to the principal focus of the lens, the more distant and the larger the image.

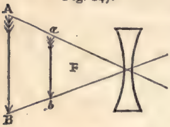
(2.) Figure 246 represents the case of an object $A\ B$ within the focal length of a convex lens. The image $a\ b$ is virtual, because made up of virtual foci; erect, because the axes do not cross between the image and the object; and larger than the object, because farther from the lens. The nearer the object to the principal focus of the lens, the more distant and the larger the image.

Fig. 246.



(3.) Figure 247 represents the case of an object $A\ B$ with a concave lens. The image $a\ b$ is virtual, because made up of virtual foci; erect, because the axes do not cross between the image and the object; and smaller than the object, because nearer the lens.

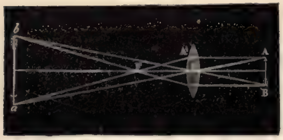
Fig. 247.



Virtual images can be seen only by looking through the lens at the object.

298. *To determine the Position of the Image.* — The position of an image may be determined by the following construction. Take any point A of the object $A\ B$ (Figure 248), and draw an axis $A\ O$ through it. Draw $A\ A'$ parallel to the principal axis. Draw a line from A' through the principal

Fig. 248.



focus F, and prolong it till it meet the axis $A\ O$. The point a, at which the lines meet, will be the position of the focus of A. By a similar construction we may locate the focus of B. Figure 249 shows the application of this construction to the case of a virtual image formed by a convex lens. Figure 250 shows the application of the same construction to the case of a virtual image formed by a concave lens.

Fig. 249.

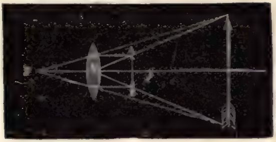
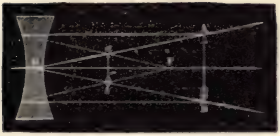


Fig. 250.



299. *Magnifying Power of Lenses.*—(1.) When an object is 40 or 50 feet distant, the rays from it which fall upon a small lens are sensibly parallel, and are brought to a focus nearly at its focal length. The image of a distant object is, therefore, formed nearly at the focal length of a lens. Hence, the longer the focal length of a lens, the larger the image it will form of a distant object.

(2.) When we can place the object as near the principal focus of the lens as we please, the shorter the focal length of a lens, the larger the image it will form. This is readily seen from Figure 251. The two lenses 1 and 2 are represented as in the same position. F' is the principal focus of the first lens, and F'' that of the second lens. $A\ B$ represents the same objects placed near the principal

focus of each lens, so that each will form an image of it at the same distance on the other side of the lenses. The

Fig. 251.

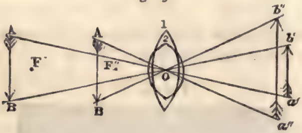
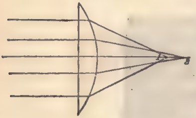


image $a' b'$, formed by the first lens, is seen to be smaller than the image $a'' b''$, formed by the second lens.

300. *Spherical Aberration.*—The rays which pass through an ordinary lens near the margin are brought to a focus a little nearer the lens than those which pass through the lens near the centre, as is shown in Figure 252. This action of the lens is called *spherical aberration.* It causes the image to appear blurred. It can be obviated only by grinding the lens to a special form, which can be exactly ascertained only by trial.

Fig. 252.



301. *Chromatic Aberration.*— An ordinary lens not only refracts, but also disperses the rays of light. The effect of this dispersion is shown in Figure 253. The violet rays, which are most refrangible, are brought to a focus at 1, while the red rays, which are least refrangible, are brought to a focus at 2. The other rays are brought to a focus between these points. This action of the lens is called *chromatic aberration.* It causes the image to be fringed with colors. It can be overcome by combining a convex lens of crown glass with a concave lens of flint glass, which

Fig. 253.

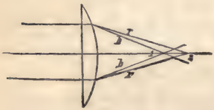
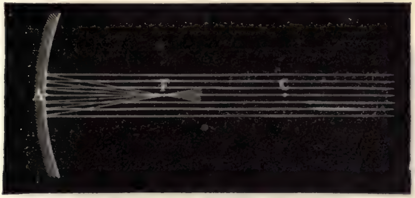


Fig. 254.

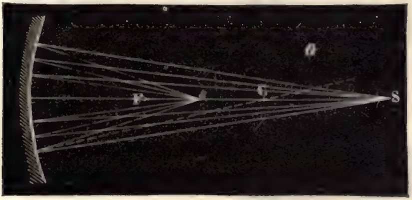
has an equal dispersive power, but a smaller refractive power. Such a combination of lenses is called an *achromatic lens.* It is shown in Figure 254.

Fig. 255.



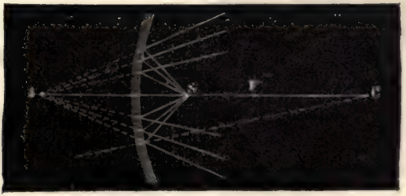
302. *Concave Mirrors correspond to Convex Lenses.* — Lenses act by *refraction*, and mirrors by *reflection.* The

Fig. 256.



result of the action of a concave mirror on rays of light is the same as that of a convex lens. A concave mirror

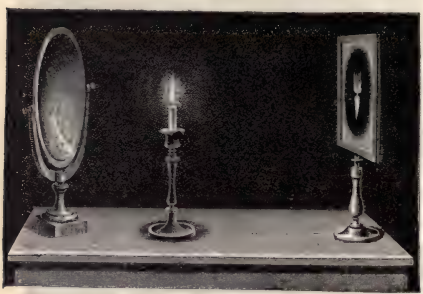
Fig. 257.



causes parallel rays after reflection to converge to a

principal focus (Figure 255); rays diverging from a point beyond the principal focus to become convergent (Figure 256); and rays diverging from a point within the principal focus to become less divergent (Figure 257).

Fig. 258.



It follows that concave mirrors will form the same images as a convex lens. The image formed by a concave mirror of an object beyond its focal length (Figure 258) is real and inverted, as in the corresponding case of a convex lens.

Fig. 259.

The image formed by a concave mirror of an object placed within its focal length (Figure 259) is virtual, erect, and larger than the object, as in the corresponding case with a convex lens.

To avoid spherical aberration, the reflecting surface of the concave mirror should

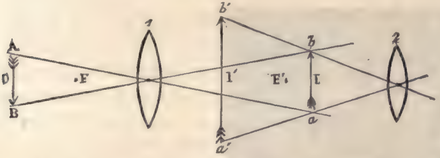
have a curvature as nearly that of the parabola as possible.

The image formed by a *convex* mirror is virtual, erect, and smaller than the object, as in the case of a *concave* lens.

F. Optical Instruments.

303. *Simple Microscope.* — A *simple microscope* consists of a convex lens mounted in any convenient way. The object to be examined is placed a little within its focal length, and the image seen on looking through the lens is virtual, erect, and larger than the object. The shorter the focal length of the lens, the greater the magnifying power of the microscope. When great magnifying power is desired, it is better to use two or more convex lenses

Fig. 260.

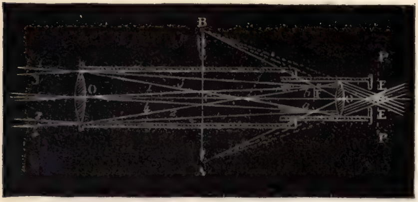


than a single lens of greater curvature. The lenses are combined so as to act as a single lens, and they give a larger and flatter field with less spherical aberration than a single lens of the focal length of the combination.

304. *Compound Microscope and Celestial Telescope.* — The combination of lenses employed in these two instruments is shown in Figure 260. *A B* is the object; 1 is the *objective* lens, 2 is the *eye-piece*, *a b* is the image formed by the objective, and *a' b'* is the image formed by the eye-piece. The object is beyond the focal length of the objective. The first image is real, inverted, and either larger or smaller than the object according to the distance of the object. The rays which meet at every point of the first

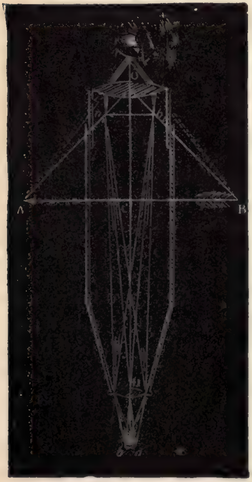
image cross and diverge in front of the image as from an object. The eye-piece is a simple microscope for examin-

Fig. 261.



ing this image as if it were an object. The image formed by the eye-piece is virtual, erect as compared with the first image, and larger than that image. It is inverted, as compared with the object, and whether larger or smaller than the object depends upon the size of the first image compared with that of the object.

Fig. 262.



A *telescope* is an instrument for examining distant objects. With the telescope the first image is smaller than the object, and increases in size with the focal length of the objective. Hence for powerful telescopes the objective is ground flat, so as to have as great focal length as possible, and made as large as possible, to admit

the greatest possible amount of light. The largest objectives now made are 26 and 30 inches in diameter, with a focal length of from 30 to 40 feet. They are made achromatic.

A *microscope* is an instrument for examining minute objects. The object, being under our control, can be placed as near the lens as we please, and hence the first image will be larger than the object, and the less the focal length of the objective the larger the image. Hence, for a powerful microscope, the objective is made of as short a focal length as possible, and since it curves very rapidly it must be very small.

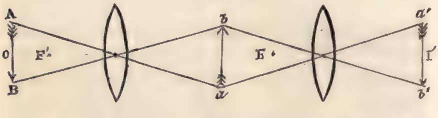
The objective and eye-piece of the telescope and microscope are mounted in a tube (Figures 261 and 262). The eye-piece is movable, and adjusted so that the final image is about 10 inches from the eye, the point of most distinct vision.

305. *The Magnifying Power of the Telescope and of the Microscope.* — The magnifying power of a telescope is the ratio of the apparent size of the final image to that of the object at its actual distance; that is, if the angle subtended by the final image is 10 times that subtended by the object at its actual distance, the telescope is said to magnify 10 diameters. Terrestrial telescopes on stands usually magnify from 20 to 60 diameters. The powers chiefly used in astronomical observation are from 100 to 500. The magnifying power of a celestial telescope is approximately equal to the quotient of the focal length of the objective divided by that of the eye-piece.

The magnifying power of a microscope is the ratio of the apparent size of the final image to that of the object at the same distance; that is, if the angle subtended by the final image is 50 times that which would be subtended by the object at the same distance, the microscope is said to magnify 50 diameters. The magnifying power of a compound microscope is the product of the magnifying powers of its objective and eye-piece. The magnifying power of a compound microscope varies from 50 to 1500 diameters.

306. *Terrestrial Telescope.* — In the celestial telescope objects are always seen inverted; but this causes no inconvenience in observing the heavenly bodies. To make terrestrial objects appear erect, a second objective is used

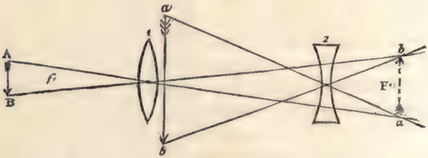
Fig. 263.



to invert the image formed by the first (Figure 263). *A B* is the object; *a b*, the image formed by the first objective, which falls without the focal length of the second objective; and *a' b'*, that formed by the second objective. Both images are real, and the second image is erect as compared with the object. One or both of these objectives may be compound.

307. *The Opera-Glass.* — The objective of an opera-glass is a convex lens, like that of the ordinary telescope, but the eye-piece is a concave lens. This lens is placed so that the real image of the objective would fall beyond it and outside of its principal focus (Figures 264 and 265).

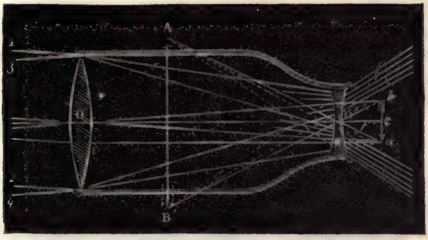
Fig. 264.



A B is the object; 1 the objective, 2 the eye-piece, *a b* the image that would be formed by the objective alone, and *a' b'* the image formed by the eye-piece. The rays which meet the eye-piece from the objective are converging to

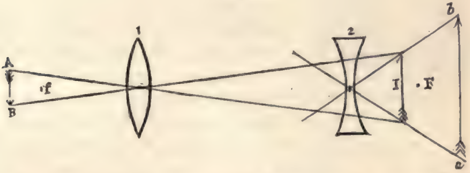
points between a and b. The final image $a'b'$ is virtual, erect, and larger than the first image would have been. The two tubes of an opera-glass are exactly alike. They are used because it is less fatiguing to use both eyes than only one. Each tube is a Galilean telescope.

Fig. 265.



When a convex and a concave lens are arranged so that the real image of the convex lens would fall beyond the concave lens, and within its focal length, as shown in Figure 266, the point of convergence being within the focal length of the concave lens, the image $a\ b$ that would be formed by that lens will be real and larger than the first image. This arrangement of lenses is sometimes used for projecting images on a screen.

Fig. 266.

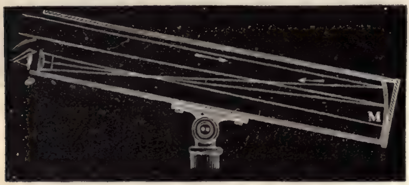


308. *Reflecting Telescope.* — In reflecting telescopes, the place of an object-glass is supplied by a concave mirror, called a *speculum*, usually composed of solid metal. The real and inverted image which it forms of distant objects

is, in the Herschelian telescope, viewed directly through an eye-piece, the back of the observer being towards the object and his face towards the speculum (Figure 267).

Achromatic refracting telescopes give much better results, both as regards light and definition, than reflectors of the same size or weight; but it has been found practicable to make specula of much larger size than object-glasses. The aperture of Lord Rosse's largest telescope is six feet, whereas that of the largest achromatic telescopes yet made is less than three feet, and increase of size involves increased thickness of glass, and consequent absorption of light.

Fig. 267.



The massiveness which is found necessary in the speculum in order to prevent flexure is a serious inconvenience, as is also the necessity for frequent repolishing, — an operation of great delicacy, as the slightest change in the form of the surface impairs the definition of the images. Both these defects have been to a certain extent remedied by the introduction of glass specula, covered in front with a thin coating of silver. Glass is much more easily worked than speculum-metal, and is only one third as heavy. Silver is also much superior to speculum-metal in reflecting power, and when it is tarnished it can be removed and renewed without liability to change of form in the glass.

309. *The Camera Obscura.* — The *camera obscura* is a dark chamber having a movable screen within it, and a convex lens fitted into an opening in front. This lens forms a real inverted image of the objects in front, which is received upon the screen. If the objects in the external

landscape depicted are all at distances many times greater than the focal length of the lens, their images will all be formed at sensibly the same distance from the lens, and may be received upon a screen placed at this distance. In order to receive the image on a horizontal table, a lens of the form shown in Figure 268 is sometimes used at the top of the camera. The rays from external objects are first refracted at the convex surface, then totally reflected at the back of the lens, which is plane, and finally emerge through the bottom of the lens, which is concave, but with a larger radius of curvature than the first surface. The two refractions produce the effect of a converging meniscus. The camera obscura employed by

Fig. 268.

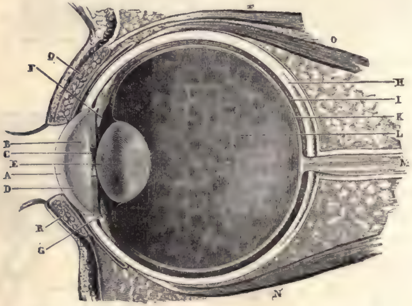
photographers (Figure 269) is a box MN, with a tube A B in front, containing an object-glass at its extremity. The object-glass is usually compound, consisting of two single lenses E L; an arrangement which is very commonly adopted in optical instruments, and which has the advantage of giving the same effective focal length as a single lens of smaller radius of curvature, while it permits the employment of a larger aperture, and consequently gives more light. At G is a slide of ground glass, on which the image of the scene to be depicted is thrown, in setting the instrument. The focusing is performed in the first place by sliding the part M

Fig. 269.

of the box in the part N, and finally by the pinion V, which moves the lens. When the image has thus been rendered as sharp as possible, the sensitized plate is substituted for the ground glass.

310. *Lantern for Projection.* — The lantern is now extensively used by teachers and lecturers for projecting experiments, diagrams, and views of various kinds upon the screen. This lantern is a kind of reversed camera. Some intense artificial light, as the lime light or the electric light, is enclosed in an opaque box. A convex lens, called the *condenser*, fixed in an opening in the front of the box, condenses the light upon the transparent picture or object to be projected. In front of this object is a tube containing a combination of lenses exactly like those used with the camera. These form a real inverted image of the object on the distant screen. Owing to the distance of the screen, the image is many times as large as the object.

Fig. 270.



311. *The Eye.* — The human eye (Figure 270) is a nearly spherical ball, capable of turning in any direction in its socket. Its outermost coat is thick and horny, and is opaque except in its anterior portion. Its opaque portion H is called the *scle-*

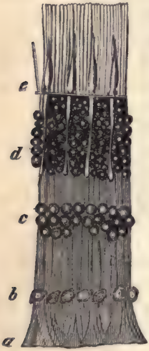
rotic coat, or in common language the white of the eye. Its transparent portion A is called the *cornea*, and has the shape of a very convex watch-glass. Behind the cornea is a diaphragm D, of annular form, called the *iris*. It is colored and opaque, and the circular aperture C in its centre is called the *pupil*. By the action of the involuntary muscles of the iris, this aperture is enlarged or contracted on exposure to darkness or light. The color of the iris is what is referred to when we speak of the color of a person's eyes. Behind the pupil is the *crystalline lens* E, which has greater convexity at back than in front. It is built up of layers or shells, increasing in density inwards. This latter circumstance tends to diminish spherical aberration. The cavity B between the cornea and the crystalline is called the *anterior chamber*, and is filled with a watery liquid called the *aqueous humor*. The much larger cavity L, behind the crystalline, is called the *posterior chamber*, and is filled with a transparent jelly called the *vitreous humor*, enclosed in a very thin transparent membrane. The posterior chamber is enclosed, except in front, by the *choroid coat* I, which is saturated with an intensely black and opaque mucus, called the *black pigment*. The choroid is lined except in its anterior portion, with another membrane K, called the *retina*, which is traversed by a ramified system of nerve filaments diverging from the optic nerve M.

It is clear, from the above description, that a pencil of rays entering the eye from an external point will undergo a series of refractions, first at the anterior surface of the cornea, and afterwards in the successive layers of the crystalline lens, all tending to render them convergent. A real and inverted image is thus formed of any external object to which the eye is directed. If this image falls on the retina, the object is seen; and if the image thus formed on the retina is sharp and sufficiently luminous, the object is seen distinctly.

312. *The Adjustment of the Eye.* — As the distance of an image from a lens varies with the distance of the object, it would be possible to see objects distinctly at only one particular distance, were there not special means of adjustment in the eye. Persons whose sight is not defective can see objects in good definition at all distances beyond a certain limit. When we wish to examine the minute details of an object to the greatest

advantage, we hold it at a particular distance, which varies in different individuals, and averages about eight inches. As we move it farther away, we experience rather more ease in looking at it, though the diminution of its apparent size renders its minuter features less visible. On the other hand, when we bring it nearer to the eye than the distance which gives the best view, we cannot see it without more or less effort; and when we have brought it nearer than a certain lower limit (averaging about six inches) we find distinct vision no longer possible. In looking at very distant objects, if our vision is not defective we have very little sense of effort. These phenomena are in accordance with the theory of lenses, which shows that when the distance of an object is a large multiple of the focal length of the lens, any further increase, even up to infinity, scarcely alters the distance of the image; but that, when the object is comparatively near, the effect of any change of its distance is considerable. There has been much discussion among physiologists as to the precise nature of the changes by which we adapt our eyes to distinct vision at different distances. Such adaptation might consist either in a change of focal length or in a change of distance of the retina. Observations in which the eye of the patient is made to serve as a mirror, giving images by reflection at the front of the cornea, and at the front and back of the crystalline, have shown that the convexity of the front of the crystalline is materially changed as the patient adapts his eye to near or remote vision, the convexity being greatest for near vision. This increase of convexity corresponds to a shortening of focal length, and is thus consistent with theory.

Fig. 271.

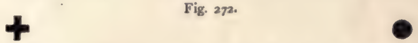


313. *The Structure of the Retina.* — Figure 271 represents a portion of the retina highly magnified, since the whole thickness of this membrane does not exceed the $\frac{1}{80}$ of an inch. The inner side *a*, which is in contact with the vitreous humor, is lined with what is called the *limiting membrane*. Externally and next to the choroid coat it con-

sists of a great number of minute rod-like and conical bodies, *e*, arranged side by side. This is the *layer of rods and cones*, and occupies a quarter of the whole thickness of the retina. From the inner ends of the rods and cones very delicate *radial fibres* spread out to the limiting membrane ; *d* and *c* are *layers of granules*. The fibres of the optic nerve are all spread out between *b* and *a*. At the entrance of the optic nerve the nerve fibres predominate, and the rods and cones are wanting. Exactly at the centre of the back of the eye there is a slight circular depression of a yellowish hue, called the *macula lutea*, or yellow spot. In this spot the cones are abundant without the rods and nerve fibres.

314. *The Action of Light on the Optic Nerve.* — The distribution of the nerve fibres over the front surface of the retina would seem to indicate that they are directly acted upon by the light ; but this is not the case. The fibres of the optic nerve are in themselves as blind as any other part of the body. To prove this we have only to close the left eye and with the right look steadily at the cross on this page, holding the book ten or twelve inches from the eye. The black dot will be seen quite

Fig. 272.



plainly as well as the cross. Now move the book slowly towards the eye, which should be kept fixed on the cross. At a certain distance the dot will suddenly disappear ; but on bringing the book still nearer it will come into view again. Now it is found upon examination that when the dot disappears its image falls exactly upon the point where the optic nerve enters the eye, and where there are no rods and cones, but merely nerve fibres. Again, the *yellow spot* is the most sensitive part of the retina, though it contains no nerve fibres.

It would appear, then, that the fibres of the optic nerve are not directly affected by the vibrations of the ether, but only through the rods and cones.

315. *The Duration of the Impression on the Retina.* — The impression made by light on the retina does not cease the instant the light is removed, but lasts about an eighth of a second. If luminous impressions are separated by a less interval, they

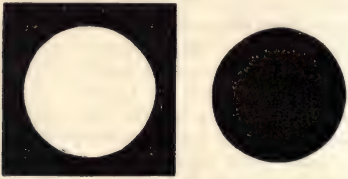
appear continuous. Thus, if a stick with a spark of fire at the end is whirled round rapidly, it gives the impression of a circle of light. The spokes of a carriage wheel in rapid motion cannot be distinguished.

The optical toy called the *thaumatrope*, or *zoetrope*, illustrates the same principle. It consists (Figure 273) of a cylindrical paper box made to rotate on an upright axis. Near the top of the box is a row of slits. The successive positions which a moving body assumes are represented in order upon a strip of paper; and this paper is put within the box, which is then whirled round rapidly. If we look at the figures through the slits, the successive positions come before the eye one after another, and the impression of each lasts till the next arrives, so that they all blend into one, and the object appears to be really going through the evolutions represented.

Fig. 273.

316. *Irradiation.* — When a white or very bright object is seen against a black ground it appears larger than it really is, while a black object on a white ground appears smaller than it really is. The two circles given in Figure 274 illustrate this.

Fig. 274.



The black one and the white one have just the same diameter. This effect is called *irradiation*. It arises from the fact that the impression produced by a bright object on the retina extends beyond the outline of the image. It bears the same relation to the space occupied by the image as the duration of the impression does to the duration of the image.

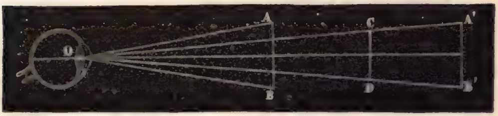
317. *The Optical Axis and the Visual Angle.* — A line drawn

from the centre of the yellow spot through the centre of the pupil is called the *optical axis.* When we look at any object we must turn the eye so as to direct this axis towards it. This enables us to appreciate the *direction* of the object.

We have seen that the image of a candle or other object, formed by a convex lens, is contained between lines drawn from the extremities of the object through the centre of the lens. In the same way the image of an object on the retina is contained between lines drawn from the extremities of the object through the centre of the crystalline lens. The angle contained between lines thus drawn is called the *visual angle* of the object, and of course measures the length of the image on the retina. All objects which have the same visual angle form images of the same length on the retina.

318. *How we estimate the Size of a Body.* — The visual angle evidently gives us no information as to the real size of a body; for we see from Figure 275 that the visual angle of a body diminishes as its distance increases, and also that bodies at different distances may have the same visual angle, though they are not of the same size. Thus, $A\ B$ and $A'B'$ are the same object; but $A'B'$, which is farther off, has the smaller visual angle. Again, $C\ D$ and $A'B'$ have the same visual angle, but $A'B'$ is the larger. We must, then, know the distance of a body, in order to estimate its size; but when we know this distance, we estimate its size instinctively. Thus, a chair at the farthest end of the room has a visual angle only half as large as a chair at half the distance, yet we cannot make it seem smaller if we try. If we are in any way deceived as to the distance of an object, we are also deceived as to its size.

Fig. 275.



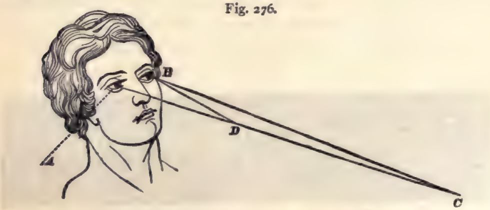
319. *How we estimate the Distance of an Object.* — If we refer to Figure 276, we see that when the eyes are directed to a distant object, as C, they are turned inward but slightly, while

they are turned inward considerably when directed to the nearer object D. The muscular effort we have to make in thus turning the eyes inward so as to direct them upon an object is one of the best methods we have of estimating its distance.

Again, we have seen that we have to adjust the eye for different distances, and the effort we have to make in this adjustment helps us to judge of the distance.

We also judge of the distance of an object from the distinctness with which we see it. The more obscure it is, the more distant it seems. It is for this reason that objects seen in a fog sometimes appear enormously large. They appear indistinct, and we cannot rid ourselves of the impression that they are far off; and hence they seem large, though they may really be small and near us.

Fig. 276.



The celebrated "Spectre of the Brocken," seen among the Hartz Mountains, is a good illustration of the effect of indistinctness upon the apparent size of an object. On a certain ridge, just at sunrise, a gigantic figure of a man had often been seen walking, and extraordinary stories were told of him. About the year 1800 a French philosopher and a friend went to watch the spectre. For many mornings they looked for it in vain. At last, however, the monster was seen, but he was not alone. He had a companion, and, singularly enough, the pair aped all the motions and attitudes of the two observers. In fact, the spectres were merely the shadows of the observers upon the morning fog, which hovered over the valley between the ridges; and because the shadows, though near, were very faint, the figures seemed to be distant, and like gigantic men walking on the opposite ridge.

When we know the real size of an object, we judge of its distance from the visual angle; but we judge of the distance of unknown objects mainly by comparing it with the distance of known objects.

This is one reason why the moon appears larger near the horizon than overhead, though she is really nearer in the latter case. When she is on the horizon, we see that she is beyond all the objects on the earth in that direction, and therefore she seems farther off than when overhead, where there are no intervening objects to help us to judge of the distance.

320. *Why Bodies near us appear Solid.* — Hold any solid object, as a book, about a foot from the eyes, and look at it first with one eye, and then with the other. It will be seen that the two images of the object are not exactly alike. With the right eye we can see a little more of the right side of the object, and with the left eye a little more of its left side. It seems to be the blending of these two pictures which causes objects to appear solid.

The principle just stated explains the action of the *stereoscope*. Two photographs of an object are taken from slightly different points of view, so as to obtain pictures like those formed in the two eyes. These photographs are placed before the eyes in such a manner that each eye sees only one, but both are seen in the same position. This is effected by the arrangement shown in Figure 277. The pictures are placed at *A* and *B*. The rays of light from them fall upon the lenses *m* and *n*, and in passing through them are bent so that they enter the eye as if they came from the direction *C*. The lenses are portions of a double-convex lens, arranged as shown in the figure.

Fig. 277.

321. *Near-sighted and Far-sighted Eyes.* — To see an object distinctly, a clear image of it must be formed on the retina. It

has been seen that the eye has the power of adjusting itself so as to form distinct images of objects at different distances. When, however, an object is brought quite near the eye, it becomes indistinct, showing that there is a limit to this power of adjustment. The rays are now so divergent that the lens cannot bring them to a focus on the retina. The nearest point at which a distinct image is formed upon the retina is called the *near point* of vision, and the greatest distance at which such an image is formed is called the *far point*. In perfectly formed eyes the near point is about 3½ inches from the eye, and the far point is infinitely distant. In such eyes parallel rays are brought to a focus exactly at the retina when the eye is at rest, that is, when the crystalline lens is of its natural convexity. The pupil of the eye is so small that the rays which fall upon it from objects 18 or

Fig. 278.

20 inches distant diverge so little that they may be regarded as parallel. The distance of the near and far points, however, is not the same for all eyes. In some cases the near point is considerably less than 3½ inches from the eye, while the far point is only 8 or 10 inches. In other cases the near point is 12 inches from the eye, and the far point infinitely distant. The former are called *near-sighted* eyes; the latter, *far-sighted* ones.

It was once thought that near-sightedness was due to the too great convexity of the cornea or the crystalline lens, or of both, and far-sightedness to the too slight convexity of the same. But actual measurement has shown that their real cause lies in the shape of the eyeball, which in far-sighted people is flattened, and in near-sighted people elongated, in the direction of the axis. In Figure 278 the curve N shows the form of the *normal* or

perfect eye, N' of the far-sighted eye, and N'' of the near-sighted eye. In this figure the eye is represented as at rest, and we see that the parallel rays A and A are brought to a focus on the retina of the normal eye, while only the convergent rays A' and A' are brought to a focus on the retina of the far-sighted eye, and only the divergent rays A'' on the retina of the near-sighted eye.

A'', then, is the far point for the near-sighted eye, since the lens has now its least convexity; and this point must be within 18 or 20 inches, since the rays from an object at a greater distance are virtually parallel, and cannot be brought to a focus on the retina. The *near* point must be less than for the normal eye, since the retina is farther from the lens, and therefore rays of greater divergence can be brought to a focus upon it. In the far-sighted eye the retina is nearer the lens than in the normal eye; hence the near point must be farther away. While, then, the normal eye sees distant objects distinctly without adjustment, the far-sighted eye must adjust itself to see such objects.

The defect of far-sighted eyes can be in a great measure remedied by wearing convex glasses, which help to bring the rays to a focus on the retina, and thus diminish the distance of the near point. The defect of near-sighted eyes can be remedied by the use of concave glasses, which render parallel rays divergent, and thus increase the distance of the far point.

322. *Old Eyes.* — As the eye grows old it loses its power of adjustment, the crystalline lens becoming less elastic; hence old eyes can see distinctly only distant objects. This, however, is a very different thing from far-sightedness. In the far-sighted eye there is no lack of power to change the convexity of the lens; but this power becomes useless because of the distance of the retina.

This defect of vision, caused by age, can be remedied by the use of convex glasses.

G. Color.

I. THEORY OF COLOR.

323. *The Three Fundamental Qualities of Color.* — The three fundamental properties upon which all the varied characteristics of color depend are *hue*, *purity*, and *brightness*.

The *hue* of color depends upon the length of the luminous waves, and corresponds to pitch in sound. In the spectrum of an incandescent solid we have all possible hues from the red through the green to the violet. Names have been given to only a few of the more prominent of these innumerable hues. These prismatic hues are simple. Other hues, as for instance the purples, are compound; that is to say, they are produced by the mingling of two or more sets of wave-lengths.

By the *purity* of a color or hue we mean its freedom from admixture with white light. Most natural and artificial colors are found, on analysis by the spectroscope, to contain a greater or less proportion of white light blended with their fundamental hue. The presence of the white light gives the hue a certain *tint* which varies with the amount of the light present. The more white light present, the paler the color. By the *brightness* of a color we mean the amount of light in it. If one colored surface diffuses twice as much light as another, its color is said to be twice as bright. When a color is at once pure and bright, it is said to be *intense* or *saturated*.

324. *The Ideal Color-Disc.* — Every possible hue of color would be represented on a disc the color of which changed by insensible gradation from the red through the green to the violet, and then around through the purple to the red again. The series of hues from the red through the green to the violet would be those of the spectrum, while the complementary series of hues from the violet through the

purple to the red have no representative among the prismatic colors. As such a disc can have only an ideal existence it is called the *ideal color-disc.*

325. *The Color Chart.* — If the ideal color-disc were divided into ten equal sectors, and each sector colored with its mean hue (the hue that would result from the blending of all the hues of the sector), there would be obtained the ten following colors: *red, orange, yellow, yellowish green, green, bluish green, turquoise blue, ultramarine, violet,* and *purple.* The position of these colors on the disc is shown in Figure 279. The disc thus divided and colored is called the *color chart.*

Fig. 279.

The colors of opposite sectors are *complementary* colors, that is, colors that would produce white when blended. We thus obtain the five prominent pairs of complementary colors, as follows: —

Red and bluish green,
Orange and turquoise blue,
Yellow and ultramarine,
Yellowish green and violet,
Green and purple.

Had the disc been divided into 20 equal sectors, and each sector colored as above, there would have been produced 10 pairs of complementary colors; if into 40 equal sectors, 20 pairs of complementary colors; and so on. In fact, were any diameter drawn through the ideal color-disc, the colors on the disc at the opposite ends of the diameter would be complementary colors. Comparatively few of the hues on the ideal color-disc have ever been named.

In the case of the color chart the change in color in

passing from one sector to the next is much greater in the neighborhood of the purple than in that of the green.

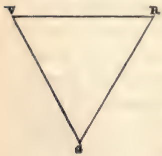
326. *The Color Scale.* — In order to have the change in color equal in passing from one sector to the next in every part of the disc, it is necessary to make the sectors smaller in the region of the purple than in that of the green. In Figure 280 the disc is shown as divided into 12 unequal sectors for equal change in color from sector to sector. Each sector is colored as before. The colors obtained are *vermilion*, *orange*, *yellow*, *yellowish green*, *green*, *bluish green*, *turquoise blue*, *ultramarine*, *bluish violet*, *purplish violet*, *purple*, and *carmine*. This arrangement of the disc is called the *color scale*.

Fig. 280.

It may be stated as a general fact that the colors which are nearest together on the scale form the poorest combinations, while those farthest apart form the best. When the colors are equally pure and bright, and cover equal extents of surface, the best possible combination that can be formed with any color on the scale is that formed with the *sixth* color from it. The two colors that will under similar conditions combine best with any color are the *third* colors on each side of that color on the scale.

327. *The Three Primary Colors.* — It is found that all possible hues of color can be obtained by mixing in various proportions the three hues, *red*, *green*, and *violet*. Hence these three hues are called the three *primary colors*. In Figure 281 these three colors are arranged at the three angles of the triangle *R G V*. This arrangement is called the *color triangle*.

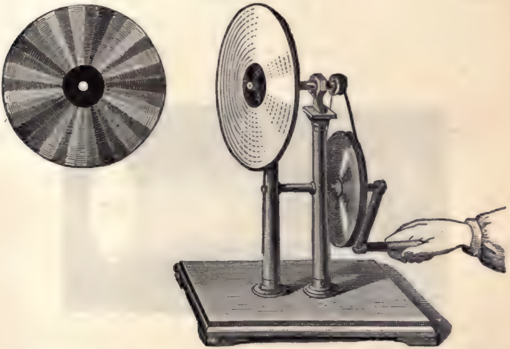
Fig. 281.



By mixing the hues red and green in

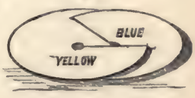
various proportions, all the hues from red to green can be obtained. In this admixture the proportion of the red must steadily decrease and that of the green increase in passing from the red to the green. By a similar admixture of green and violet we can obtain all the hues that lie between the green and violet; and of violet and red, all the hues of purple which lie between the red and violet opposite the green. The three primary hues may be blended by means of the apparatus shown in Figure 282.

Fig. 282.



Three colored discs of thick paper are employed with it. One of the discs must be colored vermilion red, another emerald green, and the third violet (Hofmann's violet B B). Each disc has a small hole in it at the centre, and is cut open on one side from the margin to the centre. Any two of the discs may be combined by holding them up with their cut places opposite, and slipping one of them into the other (Figure 283). By turning around the

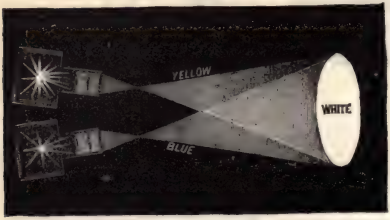
Fig. 283.



discs thus combined the amount of each disc exposed may be varied at pleasure.

Place the red and green discs thus combined upon the rotating disc, and put it into rapid rotation by turning the crank. The hues of the exposed portions of the two discs will be blended in the eye by the persistence of vision, the impression of the color of the exposed portion of each disc remaining on the retina till after the exposed portion of the other disc comes round into its place. By changing the proportions of the surfaces exposed by the discs, the proportions of the two hues in the admixture can be varied at pleasure. In a similar way the colors green and violet and red and violet may be blended in various proportions.

Fig. 284.



328. *Difference between mixing Hues and mixing Pigments.*— Fill two glass tanks having parallel sides, one with a solution of aniline yellow, and the other with an ammoniacal solution of sulphate of copper, and place each in front of a lantern, so as to project two colored discs on the screen. One of these will be yellow and the other blue. Turn the lanterns till the two colored discs overlap or coincide. The resulting disc is white (Figure 284). In this case the hues are mixed without any mixture of substance.

Now mix the two solutions by pouring some of each into a third cell, and place this cell before one of the lan-

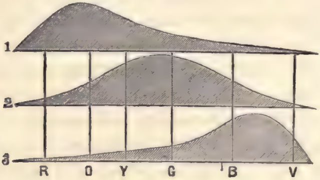
terns. The disc on the screen will be green. The same result would be obtained were two cells, each containing one of the solutions, placed in front of one of the lanterns so that the light from the lantern must pass through both solutions.

On analyzing, by means of a prism, the light which passes through each solution, it will be found that the yellow solution absorbs and quenches all the rays of the spectrum above the green; and the blue solution, all those below the green. Green is the only color which is not absorbed by either substance. Hence, when light is allowed to pass through both substances, either by mixing them in one cell, or by placing them in separate cells, one in front of the other, they absorb and quench all the colors except the green, and therefore the disc obtained on the screen is green. The hues of two colored substances are never blended when the substances themselves are mixed. One of the substances always absorbs and quenches a part of the rays which escape from the other.

329. *The Theory of Color Perception.* — The theory of color perception at present accepted by nearly all authorities is that of Young modified by Helmholtz, and sometimes called the *Young-Helmholtz theory.* According to this theory there are three primary color-sensations, namely, those of red, green, and violet, and all our perceptions of color arise from various combinations of these three. Each minute portion of the retina is capable of receiving and transmitting these three sensations, because it is supplied with three nerve fibrils, one of which is especially adapted for the reception of each of these sensations. "One set of these nerves is strongly acted on by long waves of light, and produces the sensation we call red; another set responds most powerfully to waves of medium length, producing the sensation which we call green; and, finally, the third set is strongly stimulated by short waves, and generates the sensation known as violet. The red of the spectrum, then, acts powerfully on the first set of these nerves; but, according to the theory, it also

acts upon the other two sets, but with less energy. The same is true of the green and violet rays of the spectrum; they each act on all three sets of nerves, but most powerfully on those especially designed for their reception. All this will be better understood by the aid of the accompanying diagram (Figure 285).

Fig. 285.



Along the horizontal lines 1, 2, 3, are placed the colors of the spectrum properly arranged, and the curves above them indicate the degree to which the three kinds of nerves are acted on by these colors. Thus we see that nerves of the first kind are powerfully stimulated by red light, are much less affected by yellow, still less by green, and very little by violet light. Nerves of the second kind are much affected by green light, less by yellow and blue, and still less by red and violet. The third kind of nerves answer readily to violet light, and are successively less affected by other kinds of light in the following order: blue, green, yellow, orange, red. The next point in the theory is that, if all three sets of nerves are simultaneously stimulated to about the same degree, the sensation which we call white will be produced." * Therefore, when the first and second sets of nerves are both excited more or less powerfully at the same time, the resulting sensation will be compound, being made up of the sensation of red and green. The hue perceived in this case will be somewhere between the red and the green. If the two compound sensations are equally intense, the hue will lie midway between red and green, and will be yellow. If the red sensation is the more powerful, the hue perceived will be nearer the red; if the green sensation is the more powerful, nearer the green. In a similar way, when the second and third

* Rood's Modern Chromatics.

sets of nerves are stimulated together, the resulting sensation will be compounded of a sensation of green and of violet. The hue perceived will lie between green and violet, and nearer the one or the other of these colors according as the one or the other of the component sensations is the more intense. So also the sensation of purple results from the blending of the two sensations of red and violet. Whether the hue is reddish purple or bluish purple depends upon whether the first or the third set of nerves is more powerfully excited.

According to the Young-Helmholtz theory, all color sensations, except those of red, green, and violet, are compound. These compound sensations may, however, be excited by a simple external agent. For instance, a single set of luminous waves, of a length midway between those of red and green, would, on entering the eye, excite the first and second set of nerves equally, and so give rise to the compound sensation of yellow. The eye would be unable to distinguish the sensation thus produced from one produced by red and green rays entering the eye together. In a similar way the sensation of any hue between the red and the green, or between the green and the violet, may be awakened either by a single set of waves or by two sets of waves.

The sensation of white is composed of the three fundamental sensations of red, green, and violet, but this sensation may be awakened by two hues, or even by two sets of waves. Were two sets of waves about midway between the red and the green and between the green and the violet to enter the eye at the same time, they would excite all three sets of nerve fibres and give rise to the sensation of white.

330. *Color-Blindness.* — There are many persons who cannot see certain colors. Such persons are said to be *color-blind.* Color-blindness usually takes the form of *red* blindness, though there are some eyes that are blind to green, and others that are blind to violet. A red-blind person can see no difference in color between a ripe strawberry and its leaf. His range of hues is limited to green and blue, and the hues produced by their combinations.

Such a person will make the most absurd mistakes in attempting to match colors, mistaking a bright scarlet for a black. As the danger signal is everywhere a red light, serious accidents have occasionally been traced to color-blindness in those employed to observe the signals.

Many persons are color-blind without being aware of the fact. This defect in the sight can often be detected only by systematic testing in the matching of colors.

It has been ascertained that about one male in every twenty-five is more or less color-blind. Comparatively few women are color-blind.

According to the Young-Helmholtz theory, color-blindness is due to the absence or the paralysis of one or other of the three sets of nerve fibres.

II. COLORS PRODUCED BY ABSORPTION AND INTERFERENCE.

331. *Colors produced by Absorption.* — Most of the colors of non-luminous bodies are produced by absorption. A small portion of the light that falls upon the body is diffused at the surface. The portion thus diffused enables us to see the surface, and is white or the color of the incident light. A large portion of the light is diffused from particles in the interior after it has penetrated the substance of the body to a slight depth. A portion of this light is absorbed and quenched in its passage through the substance of the body. It is this light which gives the body its color. The light which emerges from the body after the internal diffusion will be the light which enters the body minus that which has been quenched by absorption. The color of the body will be the color which is produced by the blending of the hues which remain in the light after it has suffered absorption by the body. It will be the complement of the color absorbed by the body. Bodies differ in color because they absorb different constituents of the white light that falls upon them, or else the same

constituents in different proportions. In either case the hue of the light which escapes from the body will be different. A painter does not create colors. He simply prepares the surface of his canvas so that it shall destroy all the colors of white light which he does not want. He produces the hue he desires by destroying its complement. Many bodies do not have the same color by gaslight as by daylight. Some of the constituents of daylight are partially or wholly wanting in gaslight. Hence the constituents which remain after absorption are not the same in the two cases. Luminous sodium vapor emits only yellow rays. Most colors disappear entirely in the light of the sodium flame alone; for in case the body absorbs the yellow rays, there are no rays remaining for it to diffuse. Strictly speaking, the color does not reside in the body, but in the light which it diffuses. A body has no color in the dark.

332. *The Colors of Soap-Bubbles.* — Brilliant colors play over the surface of a soap-bubble while it lasts, becoming richer and richer as the bubble becomes thinner. If a film of soap-suds is held on a ring before the lantern, so as to throw a beam of reflected light upon a projecting lens, an image of the film will be projected upon the screen and will appear highly colored. The colors will be in constant motion. These brilliant colors are produced by *interference.* Some of the rays of light which fall upon the film will be reflected from each surface. The rays which are reflected from the rear surface of the film will have to travel twice the thickness of the film farther than those which are reflected from the front surface. Were the thickness of the film one fourth of a wave-length, the rays reflected from the rear surface of the film would fall half a wave-length behind those reflected from the front, and the two sets would be in opposite phases on leaving the front of the film after reflection. They would consequently destroy each other. The same would be true were the thickness of the film any odd number of quarter wave-lengths.

On the contrary, were the thickness of the film half of a wave-length, one set of rays would fall a whole wave-length behind

the other set, so that the two sets of rays would be in the same phase on their return, and would, accordingly, intensify each other. They would also be in the same phase were the thickness of the film any even number of quarter wave-lengths.

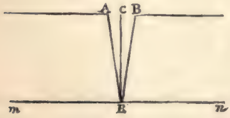
Now the thickness of the film is constantly changing at any one point, and is different at different points. Hence the two sets of rays will tend to destroy each other at some points and to intensify each other at other points; and at any one point they will tend to intensify each other one instant, and to destroy each other the next. Moreover, as the waves of the different colors differ in length, at the point where one kind of waves tend to destroy each other, other kinds of waves would tend to intensify each other. The destruction of a portion of the constituents of white light by interference in certain parts of the film gives rise to the phenomenon of color. As the film changes in thickness, the colors shift from point to point and so appear in constant motion.

Any thin film whatever will produce these colors.

333. *Diffraction Fringes.* — When a bright line of light is looked at through a narrow opening, a bright band of white light will be seen at the centre of the opening, and, parallel with this on each side, a number of colored fringes. These colored fringes are called *diffraction fringes.* The narrower the opening the broader the fringes. The fringes are due to interference.

As each wave of the ether passes through the opening, it not only pursues its direct course to the retina, but also diverges to the right and the left, tending to put in motion the whole mass of ether behind the opening. Every point of the wave which fills the opening is itself the centre of a new wave-system, which is transmitted in every direction through the ether behind the opening. These new waves would meet in opposite phases and destroy each other at certain points.

Fig. 286.

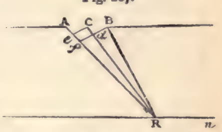


Suppose, at first, all the waves which pass through the opening are of the same length, or, in other words, that the light is monochromatic. Let $A\,B$ (Figure 286) be an enlarged section of the opening, and $m\,n$ a por-

tion of the retina. Consider first the point *R* directly in front of the opening. As the opening is very narrow, the paths by which all of the rays starting between *A* and *B* reach the point *R* will be virtually of the same length. Hence there will be no destruction of waves at this point, which will therefore appear bright. The interference of the rays will be but slight for some distance to the right and left of *R*. Hence there will be a bright band at this central point.

Next consider the point *R* (Figure 287) so situated that the paths *A R* and *B R*, by which rays from *A* and *B* reach it, differ by one wave-length. Draw *C R* from the point *C*, half-way between *A* and *B*. Also draw *B f* so as to make *f R* equal to *B R*, and *C e* parallel to it. *A f* will be the length of a wave, and *A e*, *e f*, and *c d* each the length of half a wave.

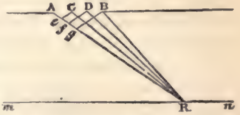
Fig. 287.



A R will be half a wave-length longer than *C R*, and every ray from *A* to *C* will be just half a wave-length longer than every corresponding ray from *C* to *B*. Hence the two sets of rays will meet in opposite phases at *R*, and will accordingly destroy each other. The point *R* will therefore be dark. The destruction of the rays will be nearly complete for some distance each side of *R*. Hence there will be a dark space at this point. There will also be a dark space at the corresponding point on the left of the opening.

Suppose the point *R* (Figure 288) so situated that the paths *A R* and *B R* by which rays from *A* and *B* would reach *R*, would differ by a wave-length and a half in length. Take the two points *C* and *D* so as to divide the opening into three equal parts. Draw *C R* and *D R*. Also draw *B g* so as to make *g R* equal to *B R*, and draw *D f* and *C e* parallel to *B g*. *A f* is the length of a wave, and *A e* of half a wave. The rays between *A* and *C* would meet those between *C* and *D* at *R* in opposite phases, and destroy them; while the rays between *D* and *B* would not be destroyed at *R*. Hence

Fig. 288.



this point would be bright, and the brightness would continue a little way on each side of R. The corresponding point on the left of the opening would also be bright.

In a similar way it may be shown that there would be complete destruction of the rays at every point whose distance from the two edges of the opening differ by any *even* number of half wave-lengths, and only partial destruction of the rays at every point whose distance from the two edges of the opening differ by any *odd* number of half wave-lengths.

The longer the waves, the farther to the right or the left the points at which there would be only partial destruction of the waves. Hence, when white light is allowed to pass through the opening, the different rays will produce bright bands at different distances to the right or the left of the central line, the blue being nearest to the central line and the red the farthest away from it. The fact that these various colored bands only partially coincide accounts for the colors of the fringe.

Fine lines ruled on glass or polished metal reflect light from their sides. At certain points the rays reflected from the opposite sides of the lines meet in opposite phases and destroy each other. The obliquity of reflection which extinguishes the shorter wave will not extinguish the longer ones. Hence colors are produced whenever light is reflected from finely ruled surfaces. These are called the colors of striated surfaces. They are beautifully illustrated by mother-of-pearl. This shell is composed of exceedingly thin layers, which, when cut across in the polishing of the shell, expose their edges, and furnish the necessary small and regular grooves.

334. *Diffraction Spectrum.* — If a piece of glass, ruled with fine lines at the rate of several thousand to the inch, is held between the eye and a bright line, so that the lines on the glass shall be parallel with the lines of light, a number of spectra are seen on each side of the central line. A piece of glass ruled in this way is called a *grating*, and the spectra obtained with it are called *diffraction* spectra. These spectra may be viewed with a telescope instead of the naked eye.

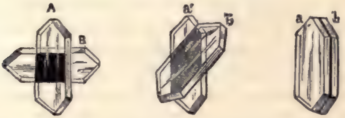
The diffraction spectrum is less brilliant than the prismatic spectrum, but it is of far greater purity, and the position of the colors in it depends solely on their wave-lengths. This spec-

trum furnishes the most accurate method of ascertaining the wave-lengths of the different colors.

III. COLORS PRODUCED BY POLARIZATION.

335. *Polarization by Plates of Tourmaline.* — Tourmaline is a semi-transparent mineral, which occurs in crystals. A plate cut from one of these crystals, with its faces parallel to the axis of the crystals, is equally transparent to ordinary light in whatever position it is held. When two such plates of tourmaline are placed together, as shown in Figure 289, the combination will be most transparent when the plates are parallel to each other, less transparent when they are oblique to each other, and wholly opaque when they are at right angles to each other. The light which has passed through one of the plates

Fig. 289.



of tourmaline is in a peculiar, unsymmetrical condition. It has acquired a kind of *two-sidedness*, so that it will pass through a second plate of tourmaline in two positions 180° apart, in which the second plate is parallel with the first, and be stopped in two positions 90° from the former, in which the second plate is at right angles to the first. Light in this condition is said to be *polarized.*

Polarized light cannot be distinguished from ordinary light by the unaided eye. In all experiments in polarization, two pieces of apparatus must be employed, one to produce polarization, and one to show it. The former is called the *polarizer*, and the latter the *analyzer*. Any apparatus that will serve for one will serve for the other also. In the case of the tourmaline plates, the plate which first receives the light is the polarizer, and the other plate the analyzer. The usual method of testing light to see whether it is polarized or not is to allow it to fall upon an analyzer, and notice whether any change of brightness occurs as

the analyzer is rotated. When the light of the blue sky is examined with an analyzer, a difference of brightness can be detected as the analyzer is rotated, especially when we look 90° from the sun. In all cases in which light is polarized, there are two positions of the analyzer, differing by 180°, which give a minimum of light, and two positions midway between these which give a maximum of light. The difference between the maximum and minimum brightness shows the completeness of the polarization of the light.

336. *The Theory of Polarization.* — The following statement of the theory of polarization, as applied to the tourmaline plates, is taken from Tyndall: "It has been already explained that the vibrations of the individual ether-particles are executed *across* the line of propagation. In the case of ordinary light we are to figure the ether-particles as vibrating in all directions, or azimuths, as it is sometimes expressed, across this line. Now, in the case of a plate of tourmaline cut parallel to the axis of the crystal, a beam of light incident upon the plate is divided into two, the one vibrating parallel to the axis of the crystal, the other at right angles to the axis. The grouping of the molecules reduces all the vibrations incident upon the crystal to these two directions. One of these beams — namely, that whose vibrations are perpendicular to the axis — is quenched with exceeding rapidity by the tourmaline. To such vibrations many specimens of the crystal are highly opaque; so that, after having passed through a very small thickness of the tourmaline, the light emerges with all its vibrations reduced to a single plane. In this condition it is what we call *plane polarized light.*"

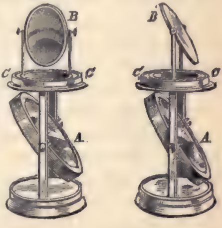
In every case of plane polarization the molecules of the ether are, according to the undulatory theory of light, all made to vibrate in the same plane.

337. *Polarization by Reflection.* — Transmission through tourmaline is only one of several ways in which light can be polarized. When a beam of light is reflected from a polished surface of glass, wood, ivory, leather, or any other non-metallic substance, at an angle of incidence from 50° to 60°, it is more or less polarized, and in like manner a reflector composed of any of these substances may be employed as an analyzer. In so

using it, it is rotated about an axis parallel to the rays which are to be tested; and the observation consists in noticing whether this rotation produces changes in the amount of reflected light.

Malus's polariscope (Figure 290) consists of two reflectors, A, B, — one serving as the polarizer and the other as the analyzer, — each consisting of a pile of glass plates. Each of these reflectors can be turned about a horizontal axis; and the upper one (which is the analyzer) can also be turned about a vertical axis, the amount of rotation being measured on the horizontal circle $C C$. To obtain the most powerful effects, each of the reflectors should be set at an angle of about 33° to the vertical, and a strong beam of common light should be allowed to fall upon the lower pile in such a direction as to be reflected vertically upwards. It will thus fall upon the centre of the upper pile, and the angles of incidence and reflection on both piles will be about 57°. The observer, looking into the upper pile in such a direction as to receive the reflected beam, will find that, as this pile is rotated about a vertical axis, there are two positions (differing by 180°) in which he sees a black spot in the centre of the field of view, these being the positions in which the upper pile refuses to reflect the light reflected to it from the lower pile. They are 90° on either side of the position in which the two piles are parallel; this latter, and the position differing from it by 180°, being those which give a maximum of reflected light.

Fig. 290.



For every reflecting substance there is a particular angle of incidence, which gives a maximum of polarization in the reflected light. It is called the *polarizing angle* for the substance, and is that particular angle of incidence which is the complement of the angle of refraction, so that the refracted and reflected rays are at right angles. This important law was discovered experimentally by Sir David Brewster.

The reflected ray, under these circumstances, is in a state of

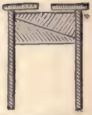
almost complete polarization; and the advantage of employing a *pile* of plates consists merely in the greater intensity of the reflected light thus furnished. The transmitted light is also polarized: it diminishes in intensity, but becomes more completely polarized, as the number of plates is increased. The reflected and the transmitted light are in fact mutually complementary, being the two parts into which common light has been decomposed; and their polarizations are accordingly opposite, so that, if both the transmitted and reflected beams are examined by a tourmaline, the maxima of obscuration will be obtained by placing the axis of the tourmaline in the one case parallel and in the other perpendicular to the plane of incidence.

338. *Polarization by Double Refraction.* — When a ray of light passes through a crystal of Iceland spar, it is usually divided into two rays, or *doubly refracted.* One of these rays obeys the law of ordinary refraction, and is called the *ordinary* ray; the other ray obeys a different law, and is called the *extraordinary* ray. As a rule, transparent crystals doubly refract light. Both of the rays furnished by double refraction are polarized, the polarization in this case being more complete than in any of the cases thus far discussed. On looking at the two images through a plate of tourmaline, or any other analyzer, it will be found that they undergo great variations of brightness as the analyzer is rotated, one of them becoming fainter whenever the other becomes brighter, and the maximum brightness of either being simultaneous with the absolute extinction of the other. If a second piece of Iceland spar is used as the analyzer, four images will be seen, of which one pair becomes dimmer as the other pair becomes brighter, and either of these pairs can be extinguished by giving the analyzer a proper position.

Since the opposite faces of a rhomb of Iceland spar are parallel, the ordinary and extraordinary rays emerge from the crystal parallel to the incident ray and to each other, but quite near together. If, however, the crystal is cut into the form of a prism in such a way that its refracting edge may be parallel to its axis, the ordinary and extraordinary rays, after leaving the prism, will diverge, so that we may easily insulate either and examine it separately. Such a prism will, of course, disperse both rays so as to produce spectra; but it may be rendered sufficiently achro-

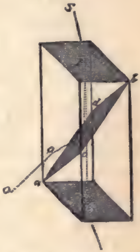
matic by combining with it a second prism of glass, whose dispersive power is different from that of the crystal. This prism is called a double-refracting prism, and is usually mounted as shown in Figure 291. This prism may be used either as a polarizer or as an analyzer.

Fig. 291.



If a rhomb of Iceland spar is cut through along the diagonal plane *a b c d* (Figure 292), and the cut faces are cemented together with Canada balsam, it forms what is known as a Nicol's prism, from the name of the inventor. The ray *S I* is doubly refracted on entering the prism. The ordinary ray is totally reflected on meeting the surface of the balsam, and passes out through the side of the prism at *o*. The extraordinary ray passes through the balsam, and finally emerges from the end of the prism in the direction of *c e*, parallel to the original direction *S I*. This prism is the most effective polarizer or analyzer yet constructed.

Fig. 292.



338. *Colors produced by Polarization.* — Very beautiful colors may be produced by the peculiar action of polarized light. If a thin film of selenite is placed between two Nicol prisms through which a powerful beam of light is passing, the image of the film glows with the richest colors. If we turn the front Nicol, the colors gradually fade and disappear, and again reappear in complementary hues. When the film is of uniform thickness, the color is uniform ; but if the thickness of the film varies, some parts of the film appear of one color and some of another. The shape and thickness of the film may be varied so as to exhibit flowers and other objects in hues unattainable by art. These colors are all produced by interference.

IV. PHOSPHORESCENCE.

339. *Phosphorescence and Fluorescence.* — Certain substances, after exposure to sunlight, will appear luminous for a long time in the dark, and that without any signs of combustion or of elevation of temperature. Such sub-

stances are said to be *phosphorescent*. The sulphides of calcium and of barium possess this property to a remarkable degree, and are therefore employed in the manufacture of *luminous* paint. Very many substances are phosphorescent to a slight degree, their phosphorescence continuing, in the majority of cases, only a fraction of a second after withdrawal from the sun's rays. Phosphorescence is excited by the violet and ultra-violet rays.

Fluorescence is essentially the same as phosphorescence. The former name is applied to the phenomenon observed while the body is actually exposed to the source of light, and the latter to the phenomenon observed after the light from the source is cut off. Phosphorescence is, so to speak, a kind of persistent fluorescence. Uranium glass is a very convenient material for the exhibition of fluorescence. A thick piece of it, held in the violet or ultra-violet portion of the solar spectrum, is filled to the depth of from ⅛ to ¼ of an inch with a faint nebulous light. A solution of sulphate of quinine is also frequently employed for exhibiting the same effect, the luminosity in this case being bluish. If the solar spectrum is thrown upon a screen freshly washed with sulphate of quinine, the ultra-violet portion will become visible by fluorescence; and if the spectrum is very pure, the presence of dark lines in this portion will be detected.

H. Conversion of Radiant Energy into Sound.

340. *Bell's Discovery.* — Mr. Graham Bell has discovered that musical sounds are developed when an intermittent beam of light is allowed to fall upon a solid, liquid, or gas under suitable conditions. The loudness of the sound varies with the nature of the substance employed and with its physical condition. A thin disc of a solid will emit a louder sound than a thick mass. The loudest sounds are produced by solids in a loose, porous, spongy condition, and by those which have the darkest and most absorbent colors.

The solids which have been found to be the most sensitive to the action of the intermittent beam are cotton-wool, worsted, and other fibrous materials, cork, sponge, platinum, and other metals in the spongy condition, and lampblack.

341. *Bell's Explanation of the Action of the Intermittent Beam upon such Substances.* — "Let us consider, for example, the case of lampblack, a substance which becomes heated by exposure to rays of every refrangibility. I look upon a mass of this substance as a sort of sponge, with its pores filled with air instead of water. When a beam of sunlight falls upon this mass, the particles of lampblack are heated, and consequently expand, causing a contraction of the air-spaces or pores among them. Under these circumstances a pulse of air should be expelled just as we squeeze water out from a sponge. The force with which the air is expelled must be greatly increased by the expansion of the air itself, due to contact with the heated particles of lampblack.

"When the light is cut off, the converse process takes place. The lampblack particles cool and contract, thus enlarging the air-spaces among them, and the enclosed air also becomes cooled. Under these circumstances a partial vacuum would be formed among the particles, and the outside air would then be absorbed, as water is by a sponge when the pressure of the hand is removed.

"I imagine that in some such manner as this a wave of condensation is started in the atmosphere each time a beam of sunlight falls upon the lampblack, and a wave of rarefaction is originated when the light is cut off.

"*We can thus understand how it is that a substance like lampblack produces intense sonorous vibrations in the surrounding air, while at the same time it communicates a very feeble vibration to the diaphragm or solid bed on which it rests.*"

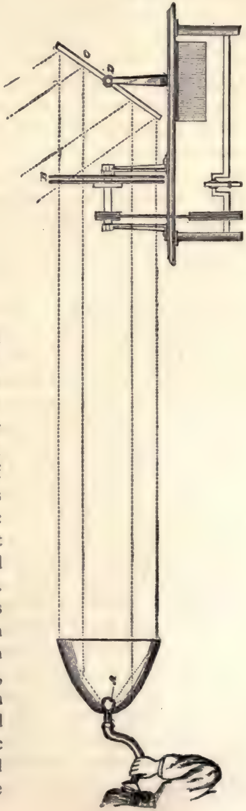
Of course the pitch of the sound emitted in any case depends upon the rapidity with which the beam of light is intercepted.

342. *The Radiophone.* — The *radiophone*, or instrument for producing sound by radiant energy, consists of an instrument for transmitting the intermittent beam, called the *transmitter*, and of an instrument for receiving the intermittent beam, called the *receiver*.

One form of the transmitter is shown in Figure 293. It consists of a reflector *C*, and of a rotating disc *B*. The disc is

Fig. 293.

Fig. 294.



pierced with a number of radial slits. Sometimes two of these discs are used, one fixed and the other capable of rotation. The beam is reflected from the mirror upon the disc. When the beam is thrown upon only one point of the disc, only a single disc is needed. On rotating the disc the beam is transmitted where it falls upon a slit and intercepted by the spaces between the slits. The more rapidly the disc is turned, the more rapidly the beam is intercepted. When the beam is reflected upon the whole disc, the double disc is necessary. In this case the beam is transmitted when the slits of the rotating disc are opposite those of the fixed disc, and intercepted when the

slits of the rotating disc are opposite the spaces between the slits of the fixed disc.

One form of the receiver is shown in Figure 294. It consists of a parabolic reflector in the focus of which is placed a glass bulb *A* containing the lamp-black or other sensitive substance. The light is reflected from the mirror *C*, is intercepted by the rotating disc *B*, and is brought to a focus upon the bulb at *A*. The bulb *A* is connected with the ear by means of a hearing-tube.

On rotating the disc *B*, a continuous musical note is heard, whose pitch rises with the speed of the rotation of the disc. By tilting the mirror *C* this continuous musical note may be broken up into long and short intervals, so as to transmit a message.

Fig. 295.

Another form of the receiver is shown in Figure 295. It consists of a hollow cone of brass, closed at the base with a flat plate of glass, and connected at the apex with an ear-tube. The sensitive material employed is enclosed in the conical cavity. Smoked wire-gauze in the receiver gives the loudest sounds.

343. *Sounds produced by Different Kinds of Rays.* — In Figure 296 is shown a kind of *spectrophone*, or instrument for examining the power of the rays in different parts of the spectrum to produce sound. The rays reflected from the mirror *A* are brought to a focus by the lens *B* upon the opening in the screen *C*, and there dispersed by a bisulphide of carbon prism *E*, suitably placed between two lenses. The rays are intercepted by the rotating disc *F*. The rays are then examined by the

receiver G, having a small opening in a diaphragm in front of the glass plate.

On using the smoked wire-gauze in the receiver, it is found that sound is produced by all the rays of the spectrum except the extreme violet. The sound rises in intensity as the receiver is passed from the violet to the red end of the spectrum, and attains its maximum far out in the ultra-red region of the spectrum. With different substances in the receiver, the portion of the spectrum capable of producing audible sounds is found to vary greatly, as well as the region of maximum intensity of sound. From numerous experiments Graham Bell has arrived at the conclusion that "*the nature of the rays that produce sonorous effects in different substances depends upon the nature of the substances that are exposed to the beam, and that the sounds are in every case due to the rays of the spectrum that are absorbed by the body.*"

Fig. 296.

It has been proposed to give the name *radiophone* to an instrument sensitive to all the rays; and the names *thermophone*, *photophone*, and *actinophone* to instruments especially sensitive to *thermal*, *luminous*, and *actinic* rays respectively.

344. *Sounds produced by Vapors.* — Many vapors have been found to be especially sensitive to the action of the intermittent beam. Tyndall was one of the first to experiment with vapors. He was engaged in a series of experiments upon the absorbent powers of different gases when, as he says, "I became acquainted with the ingenious and original experiments of Mr. Graham Bell, wherein

musical sounds are obtained by the action of an intermittent beam of light on solid bodies. From the first I entertained the opinion that these singular sounds were caused by rapid changes of temperature, producing corresponding changes of shape and volume in the bodies impinged upon by the beam. But if this be the case, and if gases and vapors really absorb radiant heat, they ought to produce sounds more intense than those obtainable from solids. I pictured every stroke of the beam responded to by a sudden expansion of the absorbent gas, and concluded that, when the pulses thus excited followed each other with sufficient rapidity, a musical note must be the result. . . . Highly diathermanous bodies, I reasoned, would produce faint sounds, while highly athermanous bodies would produce loud sounds ; the strength of the sound being, in a sense, the measure of the absorption." He found the results of his experiments to be in exact accordance with his theory.

345. *The Articulating Photophone.* — In the *articulating photophone* the intensity of the light which falls upon the receiver is made to vary in the same manner as the vibration of the spoken words. To accomplish this a thin piece of mica is used as a reflector, and is placed at the bottom of a little chamber, connected with the mouth-piece by a tube. On speaking into the mouth-piece the disc of mica is thrown into vibration. These vibrations change the form of the reflecting surface, making it more or less convex or concave as the case may be. Every change in the form of the reflecting surface changes the character of the reflected beam, making it more or less divergent or convergent as the case may be. Every change of this kind in the character of the reflected beam alters the intensity of the light that falls upon the receiver.

The general arrangement of these instruments is shown in Figure 297. Words spoken at *A* are repeated at *B*, the sound being transmitted not by pulsations of the air, but by pulsations of the reflected beam.

Fig. 297.

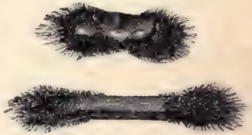
V.

MAGNETISM.

346. *Magnets.* — An iron ore was in ancient times found at Magnesia, in Asia Minor, which had a peculiar property of attracting pieces of iron. From this circumstance this peculiar property of attracting iron has been named *magnetism*, and the body possessing it is called a *magnet*. A natural magnet is now usually called a *lodestone*. It is one of the oxides of iron, and is very abundant in nature. Artificial magnets are bars of steel, sometimes straight and sometimes bent in the shape of a horse-shoe.

347. *The Poles of a Magnet.* — If a bar-magnet be plunged into iron filings and withdrawn, the filings will cling in large quantities to the ends of the bar and leave the middle bare (Figure 298). If the magnet is very thick in proportion to its length, the filings will adhere to all parts of it, but diminish in quantity rapidly towards the middle. The force of the magnet is thus seen to reside chiefly at the ends. The ends of the magnet are called the *poles;* and the middle line of the bar, where magnetic force is entirely wanting, is called the *neutral line.*

Fig. 298.



When a bar-magnet is suspended so as to turn freely, it will take a north and south direction, one end of the bar always turning towards the north and the other towards

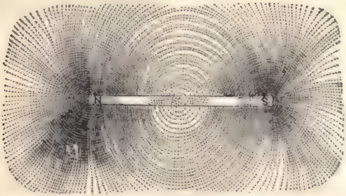
the south. The end which turns towards the north is called the *north* or *marked* pole of the magnet; and the other end, the *south* or *unmarked* pole.

If the marked pole of a magnet is presented to the marked pole of another magnet which is free to turn, there is seen to be repulsion between the poles. The same is true if the unmarked pole of one magnet is presented to the unmarked pole of another. If we present the marked pole of one magnet to the unmarked pole of another, we see attraction between the poles. *Like poles of magnets repel each other, and unlike poles attract each other.*

Fig. 299.

If a magnet $A\,B$ (Figure 299) is broken into any number of pieces, each piece will be a complete magnet with two poles, each of the strength of the original poles. In each of the four pieces into which the magnet in the figure is represented to be broken, the pole to the left, a, is the same as the pole A at the left end of the original magnet. Also the pole b at the right-hand end will be the same as the pole B of the original bar.

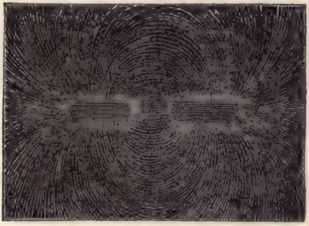
Fig. 300.



348. *Lines of Magnetic Force.* — Place a sheet of drawing-paper stretched on a frame over a bar-magnet, and sift

fine iron filings upon it. If we tap the paper gently, the filings will arrange themselves in a system of curved lines, as shown in Figure 300. If a horse-shoe magnet is held under the paper in a vertical position with its poles against the paper, the filings will form the system of curves shown in Figure 301. These curves mark the lines along which

Fig. 301.



the magnetic force acts, and show the direction and intensity of the force at each point. The curves are nearest together about the poles of the magnet, where the magnetism is most intense. The space in the neighborhood of a magnet which is pervaded by its force is called the *magnetic field*.

349. *The Curve of Magnetic Intensity in a Bar-Magnet.* — The curved line *A M B* (Figure 302) shows the relative intensity of the magnetic force in different parts of a bar-magnet, the distance of the curve from each point of the line *O M X* representing the intensity of the force at that point. Half of the curve is drawn above the line and half of it below the line, to indicate the opposite properties of the two halves of the bar.

Fig. 302.

350. *Magnetic Induction.* — If a bar-magnet is brought near a piece of soft iron, it develops magnetism in it by an action called *induction.* If iron filings are scattered over the soft iron while under the influence of the magnet, they will adhere to its ends, as shown in Figure 303. The soft

Fig. 303.

iron will have two poles and a neutral portion between them. The near end of the soft iron will be the opposite pole to that of the bar presented to it; and the far end, the other pole. Remove the magnet, and the iron filings fall off from the piece of iron, showing that the iron retains no traces of magnetism, or, at least, only very slight ones.

The attraction of pieces of iron by a magnet is always preceded by induction, the magnet developing in the portion of the iron nearest it a magnetic pole unlike its own. Hence pieces of iron are attracted with equal readiness by either pole of a magnet. A piece of iron which has become magnetic by contact with a permanent magnet may attract a second piece of iron, and this a third, and so on (Figure 304). A magnetic chain may thus be formed, each component of which has two magnetic poles. Each piece of iron in the filings which cling to the poles of a magnet becomes a magnet

Fig. 304.

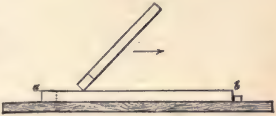
through induction, and these pieces are held together by their dissimilar poles.

A piece of steel also becomes magnetic by induction when acted upon by a magnet, but it is not so powerfully magnetized as the soft iron. It is harder to magnetize the steel than the iron, but the steel retains its magnetic power after the magnet has been withdrawn. This property of retaining magnetism is possessed in a very high degree by very hard steel, and scarcely at all by very pure and soft iron.

351. *Magnetization of Steel Bars.* — Permanent magnets are bars of steel. The steel bar may be magnetized either by the method called *magnetization by single touch*, or by that called *magnetization by double touch*.

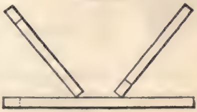
In the former method, the bar to be magnetized is laid on a board (Figure 305), near one end of which is a stop whose height is less than the thickness of the bar. The magnet is held in a sloping position and drawn over the bar several times, always in the same direction and with the same end downward. If the marked end of the magnet is held downward and drawn over the bar from *a* to *b*, the end *a* will become a marked pole. If the magnet is drawn over the bar in the opposite direction, or the other pole of the magnet is held downward, the end *b* will become the marked pole.

Fig. 305.



In the method by *double touch*, two magnets are held one in each hand with dissimilar poles downward over the centre of the bar to be magnetized, as shown in Figure 306. They are now drawn apart quite over the ends of the bar, lifted, and replaced at the centre and

Fig. 306.



again drawn over the ends. This process is repeated several times. The end of the bar over which the unmarked end of the magnet has been drawn will be the marked pole, and vice versa.

352. *Intensity of Magnetization.* — The same steel bar may be magnetized more or less intensely. As a rule, if we increase the strength of the magnetizing magnet, we increase the magnetization of the bar. In all bars there is, however, a certain limit, after which no amount of magnetic force can increase their permanent magnetism. This is called their *saturation point*, and bars so magnetized are said to be *magnetized to saturation.*

It is possible to supersaturate a bar with magnetism, that is, to give it temporarily a stronger magnetization than it can permanently retain. It is then found that, after the inducing magnetic force is removed, the magnetic force diminishes at a gradually decreasing rate until it has reached its permanent amount.

The lifting power of a magnet generally increases with its size, but small magnets are usually able to sustain a greater multiple of their own weight than large ones. Hence it has been found advantageous to construct *compound magnets*, consisting of a number of thin bars laid side by side, with their similar poles all pointing the same way. Figure 307 represents such a compound magnet composed of twelve elementary bars, arranged in three rows of four bars each. Their ends are inserted in masses of soft iron, the extremities of which constitute the poles of the system.

Fig. 307.

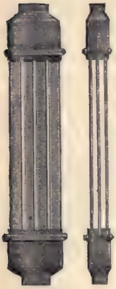


Fig. 308.

Figure 308 represents a compound horseshoe magnet, whose poles N and S support

a keeper of soft iron, from which is hung a bucket for holding weights. By adding fresh weights day after day, the magnet may be made to carry a much greater load than it could have supported originally; but if the keeper is torn away from the magnet, the additional power is instantly lost, and the magnet is able to sustain only its original load.

353. *Action of Magnetism on all Bodies.* — It has long been known that iron and steel are not the only substances which can be acted on by magnetism. Nickel and cobalt, especially, were known to be attracted by a magnet, though very much more feebly than iron, while bismuth and antimony were repelled. Faraday showed that all, or nearly all, substances, whether solid, liquid, or gaseous, are susceptible of magnetic influence, and that they can all be arranged in one or the other of two classes, characterized by opposite qualities. This opposition of quality is manifested in two ways.

(1.) As regards attraction and repulsion, iron and other *paramagnetic* bodies are attracted by either pole of a magnet, or more generally, they tend to move from places of weaker to places of stronger force. On the other hand, bismuth and other *diamagnetic* bodies are repelled by either pole of a magnet, and in general tend to move from places of stronger to places of weaker force.

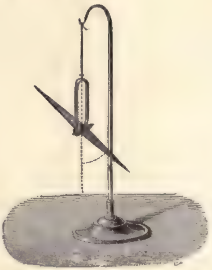
(2.) As regards orientation, a paramagnetic body when suspended between the poles of a magnet places itself *axially*, that is to say, tends to place its length along the line joining the poles, or more generally, when put in any magnetic field, tends to place its length along the line of force; hence the name *para*magnetic. A *dia*magnetic body, on the other hand, when suspended between the poles, places itself *equatorially*, that is to say, places its length at right angles to the line joining the poles, or, more generally, tends to place its length at right angles to magnetic lines of force.

354. *Magnetic Needles.* — Any magnet suspended at the centre so as to turn freely is called a *magnetic needle.* A common form of the needle is shown in the upper part of Figure 309. The needle may be suspended so as to turn in a horizontal plane, or in a vertical plane, as shown in

Figure 310. The former is called a *horizontal needle*, and the latter a *dipping needle.*

Fig. 309.

Fig. 310.



355. *Terrestrial Magnetism.* — If a steel bar is exactly balanced in a horizontal position in the frame shown in Figure 310, which is suspended by a thread without torsion, and then magnetized, it will no longer remain in equilibrium in any position in which it may be placed, but it will place itself in a particular vertical plane, and will take a particular direction in this plane. The magnetized needle takes this particular position in obedience to the force of *terrestrial magnetism.* The earth acts upon the needle as if it were itself a magnet.

The vertical plane of the needle is called the *magnetic meridian.* This plane usually lies several degrees from a north and south direction. The difference between true and magnetic north, or the angle between the geographical and the magnetic meridian, is called the *declination.* The direction of the needle in the vertical plane is seldom horizontal, but inclined by a greater or less number of degrees to the horizon. The angle which the needle makes with the horizon is called the *dip.* Both the declination and the dip of the magnetic needle are very different in differ-

ent parts of the earth. As a rule, the north pole of the needle dips at places north of the equator, and the south

Fig. 311.

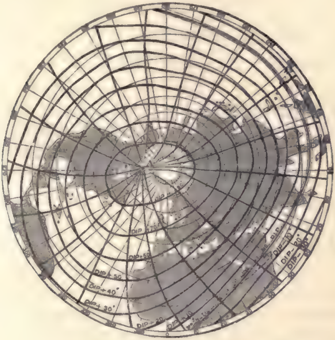
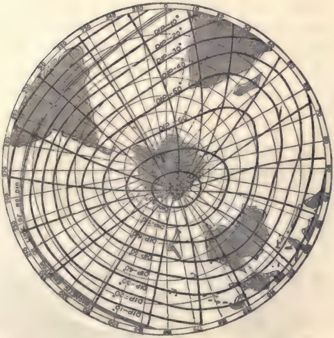


Fig. 312.

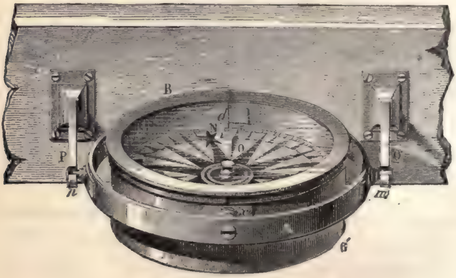


pole at places south of the equator. In the neighborhood of the equator, there is a line around the earth on which neither pole dips. This line is called the *magnetic equator*.

The dip increases as we proceed north and south from the magnetic equator. The magnetic meridians and lines of equal dip are shown in Figures 311 and 312. It will be seen that the *magnetic poles* are at some distance from the geographic poles. The magnetic pole north of the equator is a *south* magnetic pole, and vice versa.

356. *Changes in the Earth's Magnetism.* — The earth's magnetism appears to be in a state of constant fluctuation, both as regards its direction and its intensity. Some of these variations are gradual, and extend over a long series of years; these changes are called *secular.* There are also *annual* and *diurnal* variations, which seem to depend upon the position of the sun and moon with respect to the place of observation; but over and above all regular and periodic changes, there is a large amount of irregular fluctuation, which occasionally becomes so great as to constitute what is called a *magnetic storm.* Magnetic storms are not connected with thunder-storms, or any other known disturbance of the atmosphere; but they are invariably connected with exhibitions of aurora borealis, and with spontaneous galvanic currents in the ordinary telegraph-wires; and this connection is found to be so certain that, upon remarking the display of one of the three classes of phenomena, we can at once assert that the other two are observable (the aurora borealis sometimes not visible here, but certainly visible in a more northern latitude).

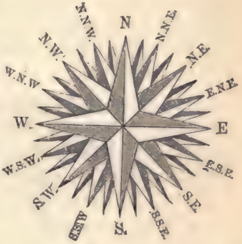
Fig. 313.



357. *Mariner's Compass.* — The magnetic action of the earth has received its most important application in the *mariner's compass.* This is a declination compass used in guiding the course of a ship. Figure 313 represents a view of the whole, and Figure 314 a vertical section. It consists of a cylindrical case, $B B'$, which, to keep the compass in a horizontal position in spite of the rolling of the vessel, is supported on *gimbals*. These are two concentric rings, one of which, attached to the case itself, moves about the axis $x d$ which plays in the outer ring $A B$; and this moves in the supports $P Q$, about the axis $m n$, at right angles to the first. In the bottom of the box is a pivot, on which is placed, by means of an agate cap, a magnetic bar $a b$, which is the needle of the compass. On this is fixed a disc of mica, a little larger in diameter than the length of the needle, on which is traced a star or *rose* with thirty-two branches, making the *points* of the compass (Figure 315). The branch ending in a small star (Figure 313), and marked N, is in a line with the bar $a b$, which is underneath the disc. The compass is placed near the stern of the vessel, in sight of the helmsman. Knowing the direction of the compass in which the ship is to be steered, he has the rudder turned till the direction coincides with the sight-vane passing through a line d marked on the inside of the box, and parallel with the keel of the vessel.

Fig. 314.

Fig. 315.



Neither the inventor of the compass nor the exact time of its invention is known.

VI.

ELECTRICITY.

I.

FRICTIONAL ELECTRICITY.

A. Electrical Attractions and Repulsions.

358. *Electrical Excitation.* — If a dry stick of sealing-wax is rubbed with a piece of dry flannel, or a vulcanite tube with a piece of dry fur, it acquires the power of attracting light bodies, such as bits of paper, pieces of straw, pith balls, etc. The body rubbed is said to be *electrified*, and the force which it manifests is called *electricity*. It has been found that electricity is developed whenever any two unlike bodies are rubbed together, though some bodies become electrified much more readily than others. The ancients noticed that amber, which the Greeks called *electron*, acquired the power of attracting light bodies when rubbed; hence the terms *electrified* and *electricity*.

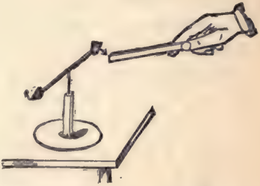
Electricity can be most readily and conveniently excited by rubbing a smooth vulcanite tube, 18 inches or so in length and ¾ of an inch in diameter, with a cat-skin; or a glass tube of the same dimensions with a silk pad, composed of three or four layers of silk, and 8 or 10 inches square. The silk pad is much more effective when covered with *amalgam*, a mixture of 1 part by weight of tin, 2 parts of zinc, and 6 of mercury. The pad should be first smeared with lard, and then the powdered amalgam sprinkled over

it. The tubes and rubbers work better when they are dry and hot.

359. *Electrical Attraction.* — A pith ball hung on a silk thread (Figure 316) will be attracted on presenting to it

Fig. 316.

Fig. 317.



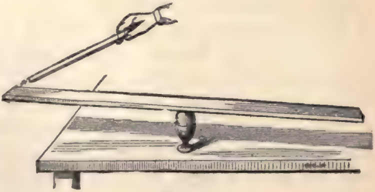
either an excited glass or vulcanite tube, without allowing it to touch the ball.

A long straw, mounted so as to turn freely on a needle stuck into a rod of sealing-wax (Figure 317), may be attracted round and round by either the excited glass or vulcanite rod.

Fig. 318.

An ordinary walking-stick placed in a wire loop, suspended by a narrow silk ribbon (Figure 318), may be pulled around by either of the excited tubes.

Fig. 319.



An ordinary lath balanced on an egg in an egg-cup (Figure 319) is sensibly attracted by the glass or vulcanite tube when electrified.

360. *Electrical Repulsion.* — Place an electrified glass tube in the loop shown in Figure 318, and present another excited glass tube to it. The tube in the loop will be repelled. An electrified vulcanite tube placed in the same loop will also be repelled on presenting a second electrified vulcanite tube to it. If the pith ball of Figure 316 is allowed to touch either the electrified glass or vulcanite tube, it will soon be repelled, and it cannot again be induced to touch the tube (Figure 320).

Fig. 320.

361. *Two Kinds of Electricity.* — If an electrified vulcanite tube is placed in the wire loop of Figure 318, and an electrified glass tube be presented to it, the vulcanite will be attracted; while, as we have seen, it will be repelled on presenting an electrified vulcanite tube to it. So, also, if an excited glass tube is placed in the loop, it will be repelled by an excited glass tube, but attracted by an excited vulcanite tube.

We thus see that there are two kinds of electricity: one appearing on glass when rubbed with silk, and the other on vulcanite when rubbed with fur. The former is called *positive*, or *vitreous* electricity; and the latter, *negative*, or *resinous* electricity.

When bodies are electrified, they are said to be *charged* with electricity. Bodies charged with like electricities repel each other, and those charged with unlike electricities attract each other.

362. *Electrification of the Rubber.* — The silk pad used in exciting the glass tube becomes negatively electrified, and the cat-skin used in exciting the vulcanite tube be-

comes positively electrified. This may be shown by the following experiments. Hang the vulcanite tube in the loop, having first carefully discharged the tube by rubbing the hand over it. Protect the silk pad from the hand with a piece of thin sheet-rubber. Excite the glass rod with the pad, and then present the pad to the vulcanite tube. It will be seen to attract the tube. Charge the vulcanite tube by friction with the cat-skin, and it will be repelled by the pad which has been used in exciting a glass tube, showing that the pad is negatively electrified. Similar experiments may be tried with the cat-skin used in exciting the vulcanite tube. Whenever electricity is developed by friction, equal quantities of both kinds of electricity are obtained, one on the body rubbed and one on the rubber.

B. Electrical Conduction and Insulation.

363. *Cottrell's Straw Electroscope.* — An *electroscope* is an instrument used for indicating the presence of electricity, and, also, for ascertaining whether the electricity is positive or negative. The straw electroscope, devised by Mr. Cottrell, is very cheap and convenient. It consists

Fig. 321.

of a small metallic disc *M* (Figure 321), supported on a rod of glass or sealing-wax *G*, and of a smaller disc *N*, of gilt-paper, above this, fastened with sealing-wax to one end of a long straw *II'*, capable of turning upon the needle *a a'* as an axis. The disc *N* is balanced by a little piece of bent wire at *I*, just heavy enough to separate *N* from *M*.

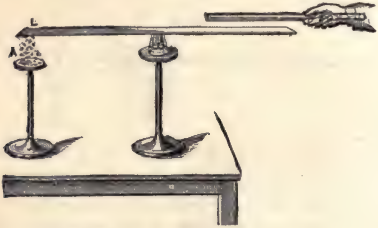
364. *Conductors.* — If a fine copper or iron wire be fastened to the disc *M* at one end, and coiled around the

glass or vulcanite tube at the other, on exciting the tube the disc *N* is at once attracted, and the end *I* of the straw thrown upward. The attraction of the disc *N* shows that the electricity excited on the tube has passed along the wire to the disc *M*. Substances which allow electricity to pass through them are called *conductors* of electricity. The metals, charcoal, acids, rain-water, linen, plants, and animals are conductors. Alcohol, dry wood, paper, and straw are *semi-conductors*.

365. *Insulators.* — If the disc *M* be connected with the glass or vulcanite tube by means of a silk thread, the disc *N* will not be attracted on exciting the tube. This shows that electricity will not pass through silk. Substances through which electricity will not pass are called *insulators*. India-rubber, vulcanite, dry paper, hair, silk, glass, wax, sulphur, shellac, and dry air are insulators.

Conductors are said to be *insulated* when they are completely surrounded by insulators. A conductor may be insulated by hanging it on a silk cord or ribbon, or by supporting it on glass, vulcanite, or sealing-wax.

Fig. 322.

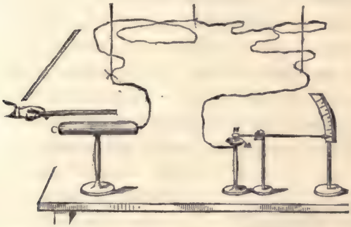


C. Electrical Induction.

366. *Electrical Induction.* — Balance a lath upon a warm tumbler or short rod of vulcanite (Figure 322). Place some bits of paper or elder pith upon a stand *A*, three or

four inches below the end *L* of the lath, and hold an excited glass or vulcanite tube near the other end of the lath without touching it. The light bodies will be attracted, showing that the lath has been electrified. Remove the excited tube and the light bodies will fall away, showing that the lath has again become neutralized. In this case the electrification of the lath took place through the air. This development of electricity by a charged body through an insulating medium is called *induction.*

Fig. 323.



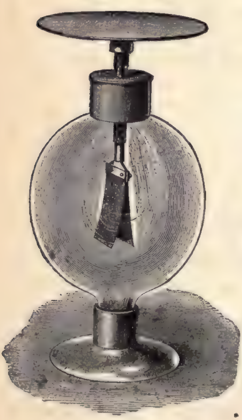
Connect one end of a small insulated conductor *C* (Figure 323) by means of a wire supported by silk loops to the disc *M* of Cottrell's electroscope. Bring an excited tube near the conductor without touching it, the disc *N* is immediately attracted. Remove the tube, and *N* is again liberated. If you touch the conductor *C* while the excited tube is held near it, the disc *N* is promptly liberated. If now you remove first the finger and then the tube, the disc will again be attracted, showing that the conductor and disc are now permanently charged. In this case the body becomes charged by induction.

367. *The Electrophorus.* — The *electrophorus* consists of a plate of wax or vulcanite (Figure 324), and of a lid of tin or brass with an insulating handle. Excite the plate by stroking it with a cat-skin, and place the lid upon it.

Owing to the unevenness of the plate, the lid will touch it at comparatively few points, but the plate will act upon the lid by induction. Remove the lid, and test it with a suspended pith ball (Figure 316). It shows no signs of electrification. Replace the lid and touch it with the finger. Remove the finger and then the lid, and present the lid to the pith ball. The ball is attracted, showing that the lid is charged. Allow the pith ball to touch the lid. It is immediately repelled, having by contact become charged with the same kind of electricity as that on the lid. Present now the plate of the electrophorus to the charged pith ball, and the ball will be attracted, showing that the lid was charged with the opposite electricity to that on the plate. *Bodies charged by contact are always charged with the same electricity as that on the body acting upon them, while bodies charged by induction are always charged with the opposite electricity to that on the body acting upon them.* The lid of the electrophorus may be charged any number of times by the plate without renewing the charge on the plate.

Fig. 324.

Fig. 325.



368. *Gold-Leaf Electroscope.* — This instrument (Figure 325) consists of two strips of gold leaf, which in a large instrument may be 4 inches long and 1 inch wide, hung together by their upper ends

to a metal rod. This rod passes through a hole in the top of a glass shade, inside of which the gold leaves hang. The rod terminates above in a brass disc or a brass ball. The glass shade serves at once to insulate the disc and leaves, and to protect the leaves from currents of air.

When an electrified body is placed in contact with the disc, it charges the disc and leaves with its own electricity, and causes the leaves to diverge. Owing to the lightness of the gold leaves, this is a very sensitive instrument for detecting the presence of small quantities of electricity.

To detect the kind of electricity on the charged body, first charge the leaves with a known kind of electricity, and then place the body to be tested in contact with the disc. If the leaves diverge more than before, the body is charged with the same kind of electricity as that on the leaves; if the leaves diverge less than before, the body is charged with the opposite electricity to that on the leaves.

If a charged body is brought near the disc without touching it, the leaves will diverge, being electrified by induction. Remove the charged body, and the leaves come together again. If we present the charged body again, and touch the disc with the finger, the leaves fall together. Remove first the finger and then the charged body, and the leaves again diverge, being charged by induction with the opposite electricity to that on the charged body.

369. *Electric Carrier.* — The *proof plane* is often employed in transferring electricity from a charged body to an electroscope. It consists of a metallic disc about 2 inches in diameter with an insulating handle. If we touch a charged body with the disc, it takes off some of the electricity from the part touched. The electricity on the proof plane may then be tested by an electroscope. A cheap and convenient electric carrier may be made by fastening a bit of tin-foil 2 or 3 inches square to one end

of a vulcanite rod 8 or 10 inches long, as shown in Figure 326. The tin-foil may be stuck to the rod with sealing-wax. The stem of the carrier in the figure is a straw stuck to a rod of sealing-wax as a handle.

Fig. 326.

370. *Two Kinds of Electricity developed in Induction.* — Charge the lid of the electrophorus, and hold it near one end of an insulated conductor. Place the carrier in contact with the lid, and then with the disc of the gold-leaf electroscope, so as to charge the leaves with the electricity on the lid. Discharge the carrier, and bring it in contact with the "far end" of the insulated conductor. Again place the carrier on the disc of the electroscope; the leaves will diverge more than before, showing that the far end of the conductor has upon it the same electricity as the inducing lid. Again discharge the carrier, and bring it in contact with the "near end" of the conductor. Remove the carrier again to the disc of the electroscope; the leaves will diverge less than before, showing that the near end of the conductor has the opposite kind of electricity to that on the lid. In a similar way, the centre of the conductor will be found to be neutral. Both kinds of electricity are always developed in

Fig. 327.

induction; the same kind of electricity as that on the inducing body being driven to the far end of the conductor, and the opposite kind being held on the near end of the conductor (Figure 327).

While the opposite electricity to that on the inducing body is held fast by the inducing body, the other elec-

tricity is driven off to the farthest possible point. If two insulated conductors are connected by a long wire, and the lid of the electrophorus is presented to one of them, the near conductor becomes charged with negative electricity and the far conductor with positive electricity. If we touch a conductor under the influence of a charged body, or connect the conductor in any way with the earth, the far end of the conductor becomes the opposite side of the earth, to which the electricity like that on the inducing body is driven. Hence, when bodies connected with the earth are acted on by induction, they have only one kind of electricity on them, and that the opposite to that on the inducing body. Hence bodies when charged by induction always become charged with the opposite electricity to that on the inducing body. In charging a conductor by induction it is necessary to remove the earth connection before removing the inducing body, else the electricity which was held fast on the conductor would escape to the earth to join the electricity which had been driven there before it.

371. *Quantity of Electricity developed by Induction.* — Every charged body develops on surrounding bodies equal quantities of opposite electricities, and an amount of each electricity equal to that on the charged body.

Suspend an ordinary tea-canister by a white silk cord and connect it by a wire with an electroscope. Lower a metallic ball hung on a silk thread and charged with electricity into the canister without touching it. The inductive action of the ball will be wholly on the canister in which it is enclosed. It will drive its own kind of electricity to the outside of the canister, and hold the opposite electricity on the inside. The leaves of the electroscope will be made to diverge by the electricity sent to the outside. Remove the ball from the canister without its having touched it. The gold leaves will fall together, showing that the canister has lost all trace of electricity. The two kinds of electricity developed by the induction of the ball must have been exactly equal, since they neutralize each other on reuniting.

Again lower the charged ball into the canister without touching it, and touch the outside of the canister with the finger, so as to allow the electricity on it to pass to the earth. The canister is now charged with the electricity held on the inside by the ball. Remove the finger and allow the ball to touch the inside of the canister, and then remove it. Neither the ball nor the canister will show any trace of electricity. The electricity on the ball has exactly neutralized that on the inside of the canister. Hence they must have been equal in amount. The electricity on the outside of the canister has already been shown equal to that on the inside; hence each is equal to that on the ball.

372. *Dielectrics.* — Induction will take place through all insulating substances. When an excited tube is brought near the disc of the electroscope, the leaves diverge because of the induction which takes place through the air. If a plate of glass, of vulcanite, of paraffin, or of shellac, is held between the tube and the disc, the leaves will still diverge because of the induction which is taking place through the plate. The substance through which induction takes place is called a *dielectric.* All insulators are dielectrics.

If a metallic plate, large enough so that induction will not take place around it, is held between the tube and the disc of the electroscope, so as to be in connection with the earth, the leaves of the electroscope will no longer diverge. No induction will take place through such a conductor. If the conducting plate were insulated, induction would appear to take place through it, because electricity would be developed on the far side of the plate by induction, and this electricity would carry on induction through the air.

Some dielectrics allow induction to take place through them more readily than others. These are said to have greater *specific inductive capacities* than the others, that is to say, greater capacities for carrying on induction. The

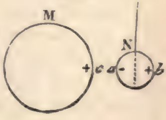
comparative inductive capacity of different insulators has been much studied in recent times, owing to its great practical importance in submarine telegraphy.

The inductive action between two conductors depends upon the distance the conductors are apart and upon the specific inductive capacity of the intervening insulator. The less the distance and the greater the specific inductive capacity of the insulator, the more powerful the inductive action.

373. *Condition of the Dielectric during Induction.* — When a body becomes charged its electricity tends to escape to surrounding bodies. If it be connected to any of these bodies with a metallic wire, the electricity will flow through this wire just as water will flow through a pipe. When the charged body is connected to a neighboring body, the electricity in its attempt to pass to the body through the dielectric throws the dielectric into a state of strain. Suppose a pipe full of water to be crossed at short intervals with elastic partitions. Should we attempt to force water through such a pipe, the partitions would be bent forward one after another; that is to say, a state of strain would be propagated through the pipe, and this state of strain would continue as long as there was an attempt to force water through the pipe. In some such way a dielectric seems to be thrown into a state of strain by the attempt of the electricity to pass through it This state of strain appears to be propagated through an insulator with the velocity of light.

374. *Attraction and Repulsion of Light Bodies.* — We now see why a charged body attracts a light body not previously charged. It first acts upon the light body by induction, inducing a change similar to its own on the far side of the body and an opposite change on the near side (Figure 328). The near side is attracted and the far side repelled; but the attracted side being nearer, the attraction is stronger than the repulsion, and the

Fig. 328.



body as a whole is attracted. On touching the charged body it gives up to it the electricity on its near side, and so becomes charged with the same electricity as that on the charged body, and is then repelled.

D. Electrical Potential.

375. *Potential.* — The term *potential* in Physics means condition as regards work. The potential of a point with respect to a force is the condition of the point as regards work done by that force. Thus the gravitation potential of a point is the condition of that point as regards work done by gravity; and the electrical potential of a point is its condition as regards work done by electricity.

376. *Gravitation Potential.* — The *absolute* gravitation potential of a point is measured by the amount of work that would be done by gravity in impeding the motion of a unit of mass, as the mass is moved from a point to an infinite distance, or in aiding its motion, as the mass is moved from an infinite distance up to the point. Thus, when we say that the absolute gravitation potential of a point is 50,000, we mean that the condition of a point is such that 50,000 units of work would be done by gravity in impeding the motion of a unit of mass if it were moved from that point to an infinite distance, or in aiding the motion of the mass if it were moved from an infinite distance to the point.

The difference in gravitation potential between two points is measured by the amount of work that would be done by gravity upon a unit of mass, in aiding or impeding its motion, were it moved from one point to the other. Thus, when we say that the difference of gravitation potential between two points is 40, we mean that the two points are in such condition that, were a unit of mass moved from one point to the other, 40 units of work would be done upon it by gravity in aiding or impeding its motion. Gravity always tends to move a body from a lower potential to a higher one. When two points are at the same gravitation potential, no work would be done by gravity upon a

body in its motion from one point to the other, because gravity would have no tendency to aid or impede its motion. Two points at the same gravitation potential are said to be at the same *level*. The term *level* is ordinarily used with gravity for potential, but a ***high level*** corresponds to a ***low potential***.

377. *Electrical Potential.* — The ***absolute*** electrical potential of a point is measured by the amount of work that would be done by electricity in aiding or impeding the motion of a small body charged with a unit of electricity, were the body moved from the point to an infinite distance, or from an infinite distance to the point. When we say that the absolute electrical potential of a point is 90, we mean that the condition of the point is such that 90 units of work would be done by electricity upon a small body charged with a unit of electricity in aiding or impeding its motion, were it moved from the point to an infinite distance, or from an infinite distance to the point. The *C. G. S.* unit of electricity is the amount of electricity that would exert a dyne of force at the distance of a centimetre.

The difference of electrical potential between two points is measured by the amount of work that would be done by electricity upon a small body charged with a unit of electricity in aiding or impeding its motion, were it moved from one point to the other. When we say that the difference in electrical potential between two points is 15, we mean that the points are in such conditions that 15 units of work will be done by electricity in aiding or impeding the motion of a small body charged with a unit of electricity, were it moved from one point to the other.

Electricity always tends to move a body charged with positive electricity from a higher to a lower potential.

When two points are at the same electrical potential, electricity does not tend to move a charged body from either point to the other, and consequently no work would be done by electricity upon a charged body in its motion from one point to the other.

When the term *potential* is used without qualification, it is always understood to mean electrical potential. *Potential* for electricity corresponds to *level* for gravity. A sur-

face all of whose points are at the same potential is called an *equipotential* surface. It corresponds to a level surface. As gravity never tends to produce motion along a level surface, so electricity never tends to produce motion along an equipotential surface. As gravity acts perpendicularly at every point to a level surface, so electricity acts perpendicularly at every point to an equipotential surface.

In electricity, the potential of the earth is taken as zero, and the potential of a point is really the difference between its potential and that of the earth. Electrical potential is usually defined in terms of positive electricity. A *positive* potential is one higher than that of the earth, and a *negative* potential is one lower than that of the earth.

378. *Electrometers.* — An *electroscope* is an instrument for detecting the presence of electricity, and for ascertaining its quality. An *electrometer* is an instrument for measuring the intensity of electrical attraction and repulsion, and for ascertaining the potential of a body.

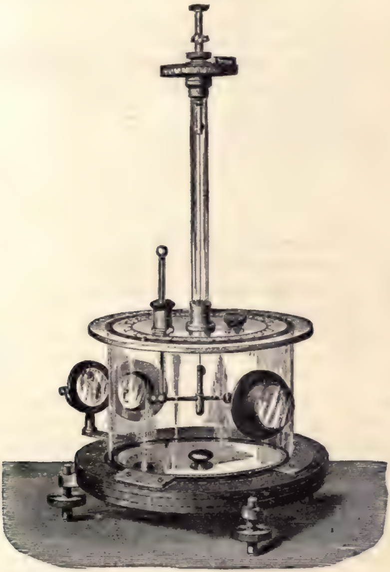
Fig. 329.

379. *Pith-ball Electrometer.* — The *pith-ball electrometer* is shown in Figure 329. A wooden stem C is mounted in a metallic socket, which can be screwed to the conductor whose electrification is to be measured. A pith ball fixed to a straw stem A hangs from a pivot at the centre of the divided arc B. Electricity is communicated from the metal socket to the ball, which is repelled. The number of degrees over which the straw passes indicates roughly the strength of the electrification of the conductor.

380. *Coulomb's Torsion Balance.* — This instrument is shown in Figure 330. A long, fine thread is suspended in a vertical tube. The thread is attached at the top to a rod which passes through the centre of a horizontal circle called the torsion circle, which is divided into degrees, and can be turned by the rod which holds the thread. A pointer on the tube indicates the

number of degrees the circle is turned. To the bottom of the thread is fastened a light rod, so as to hang horizontally. The rod carries a gilt pith ball at one end, and a similar ball at the other end to balance it. The vertical tube in which the thread is suspended stands on the centre of a horizontal glass plate,

Fig. 330.



which forms the lid of the lower part of the case in which the horizontal arm swings. Another gilt pith ball of the same size as the one on the horizontal arm is fixed to a vertical stem, which passes through the top plate, so that the two balls may be brought into contact. A circle divided into degrees is engraved on the lid of the lower case, and the base of the case is a looking-glass.

To use the instrument, the fixed pith ball is removed, and the torsion circle turned till the suspended pith ball occupies exactly the position formerly occupied by the fixed one. When it has come to rest in this position there is no torsion, and the reading of the torsion circle is taken as the zero. The fixed pith ball is then electrified and put in position, pushing the suspended ball to one side, and at the same time communicating half its charge to it. The balls now repel each other, and if the length and thickness of the thread and the strength of the charge have been properly adjusted, the suspended arm should turn through from 30° to 45°. The position of the straw is noted, and the torsion circle is turned so as to force the balls towards each other, until the straw pointer has moved through an angle equal to one division of the engraved circle. The number of degrees through which the torsion circle has been turned is then noted, and the process is repeated for several divisions, until the balls are forced rather near together. *A table can then be formed, showing the force of repulsion corresponding to each decrement of distance*, for the force overcome in each case is simply proportional to the number of degrees through which the torsion circle has been turned.

A slight modification of the arrangements will enable the force of attraction to be measured when the two balls are oppositely electrified.

By means of this instrument, Coulomb ascertained that the force of attraction or repulsion between two electrified bodies, whose sizes are very small compared with their distance apart, is inversely proportional to the square of their distances apart; and directly proportional to the product of their changes.

381. *Thomson's Quadrant Electrometer.* — Thomson's *quadrant electrometer* is the most delicate and accurate instrument that has been devised for measuring potential. Figure 331 serves to show the principle on which this instrument is constructed. *N N* is a light needle of aluminium, suspended so as to be able to turn in a horizontal plane. This needle is kept charged to a constant potential by being connected with a uniform source of electricity. Just below the needle are four metallic quadrants placed horizontally, as shown in Figure 332. Each is insulated from the one next to it, but connected with the

Fig. 331.

Fig. 332.

one diagonally opposite, as shown in Figure 331.

Suppose the needle charged with positive electricity, the unshaded quadrant connected to earth, and the shaded ones, by means of the wire *b* (Figure 331), with the conductor whose electrification is to be measured. Electricity will flow from the charged conductor to the shaded quadrant till they are of the same potential as itself. The direction in which the needle is deflected will show whether the conductor is charged with positive or negative electricity. For if the needle is deflected to the right, it must be because it is attracted by the shaded quadrants, that is, because they are charged negatively. If the needle is deflected to the left, it must be because these quadrants are charged positively, so as to repel the needle. The potential of the conductor is indicated by the amount of the deflection of the needle. The greater the deflection of the needle the higher the potential of the conductor, and the less the deflection the lower the potential.

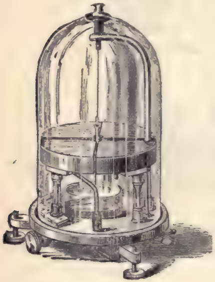
This apparatus may be used for adjusting two potentials to equality. If two similarly electrified bodies are connected with the shaded and unshaded quadrants respectively, they will tend to turn the needle opposite ways, and the deflection will depend upon the difference of potential. If now one of the electrifications be varied till there is no deflection, we shall know that the potentials have been brought to exact equality.

The form of the instrument shown in Figure 332 is only a lecture model. The inverted vessel at the top, from the interior of which the needle is suspended, is a Leyden jar for maintaining a

constant charge on the needle. The action of this jar will be described farther on.

The simplest form of the instrument that is used for real work is known as the *Elliott pattern*. It is shown in Figure 333. It differs from the lecture model in that its metal quadrants are quarters, not of a disc, but of a kind of "pill-box," inside which the needle hangs. Both sides of the needle are thus acted upon. The Leyden jar is placed at the bottom of the instrument. It contains strong sulphuric acid, and the connection between it and the needle is made by a platinum wire attached to the needle, and dipping into the acid. The acid, by its affinity for moisture, keeps the inside of the apparatus always dry. Three metal rods project from the instrument. Two (seen on the right) are connected respectively to the two pairs of quadrants, and the third (seen in the front of the figure) can be connected to the needle when it is desired to charge it with electricity. The needle is suspended by what is called a "bifilar suspension," — that is, it is hung by two fine silk threads, side by side, and about $\frac{1}{20}$ of an inch apart. After the needle has been displaced from its position of rest, these threads always tend to bring it back. The position of the needle can be adjusted by turning the head at the top of the glass case to which the threads are attached.

Fig. 333.



The instrument, when in use, is covered by a wire cage connected to earth, to protect the quadrants from the induction of neighboring charged bodies.

E. Electrical Charge.

382. *The Charge entirely on the Surface.* — Suspend a tea-canister by a silk cord, and charge it as highly as possible by means of the electrophorus or other electrical machine. Lower a brass ball hung on a silk thread into it, so as to touch the interior, and then remove it without touching the

mouth of the canister. Test the ball with an electroscope, and it will be found to have brought away no electricity from the can. Bring the ball in contact with the outside of the canister and present it to the electroscope, and it will be found to have taken electricity away from the canister. By no means can any electricity be found on the inside of a hollow conductor. Hence we conclude that the charge resides entirely on the surface; unless, of course, a charge is developed on the inside of the hollow conductor by the induction of a charged body suspended within it.

Fig. 334.

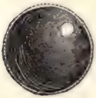


Fig. 335.

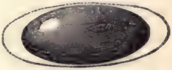
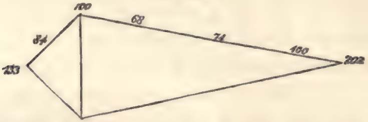


Fig. 336.

Fig. 337.

383. *Distribution of Electricity over the Surface of a Charged Body.* — Were a spherical conductor suspended on a silk thread in the centre of a large room, and charged with electricity, the charge would be distributed uniformly over the surface, as shown by the dotted line in Figure 334. The

Fig. 338.



dotted lines in Figures 335, 336, and 337 show the distribution of electricity over the surface of an ellipsoid, a cylinder with rounded ends, and a disc under similar circumstances. When the conductor is oblong, the electricity tends to accumulate at the ends. The longer and thinner the con-

ductor, the greater the accumulation at the ends. Figure 338 shows the distribution of electric charge over the surface of a conductor in the form of a double cone. The numbers indicate the intensities of the charge at different points.

384. *Density of the Charge.* — The intensity of the electrification at any point on a body is called the *electric density* at that point. The *charge* of a body is the *quantity* of electricity on it. The *density* at a point of surface, when the density is uniform, is the amount of electricity on a square centimetre of surface. When the density is not uniform, the density at any point is the amount of electricity that there would be on a square centimetre of surface, were its electricity everywhere that of the point.

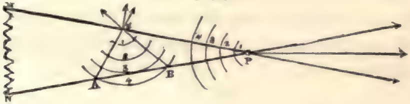
The force with which electricity endeavors to escape from any portion of surface increases with the density at that point.

The density at different points of the surface of a charged conductor may be ascertained by applying the proof plane to different portions of the surface, and seeing how much electricity it carries off with it. The density on different parts of the surface depends upon the form of the conductor and the influence of surrounding bodies. The potential of a charged conductor must be the same at every point of the surface, else the electricity would not be in a state of equilibrium, for a difference of potential would tend to move the electricity from one point of the surface to another. The potential of a body is independent of the density of its charge.

385. *Tendency of Electricity to escape from Points.* — Let MPN (Figure 339) be a section of a pointed charged conductor, and let us consider the forces tending respectively to drive off a unit of electricity from S on the side of the conductor, and from P on its point. None of the electricity on MP can act upon S so as to tend to cause it to escape from the

surface. This electricity can act on S only to urge it to the right or left along the surface. Only such portions of the electricity on the side NP as are moderately near S would tend to separate it from the conductor. None of the electricity on this side is nearer than 3 to S, and only the portion $A\ B$ is nearer than 4. Now, as the force of repulsion decreases as the square

Fig. 339.



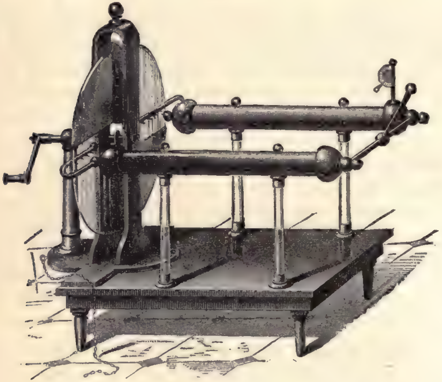
of the distance increases, and as a good deal of the electricity between A and B acts upon S obliquely to the surface $M\ P$, the component of the repulsion acting upon S perpendicularly to the surface would be very small. When we consider the whole conductor instead of the section, the nearer we come to S the more obliquely the repulsive force acts upon it, and the weaker the perpendicular component. Upon P, on the contrary, there is electricity acting at all the distances from 0 up to 4, and it is all acting very nearly in the direction that would tend to drive the electricity off from the point, as is indicated by the arrows. And this is still the case, whether we consider the whole conductor or its section. Hence there is a much greater tendency to drive electricity off from a point than from any other part of a conductor.

If a sharp metallic point is fixed to one end of a small insulated conductor, and the lid of the electrophorus charged with positive electricity is held in front of the point so as to act upon the conductor by induction, negative electricity will escape from the point to the lid, and on removing the lid the conductor will be found to be charged feebly with positive electricity. If the charged lid of the electrophorus is held near the other end of the conductor, positive electricity will escape from the point, and on removing the lid the conductor will be found to be charged feebly with negative electricity. If a plate of dry glass is

held between the lid of the electrophorus and the point, negative electricity will escape from the point to the glass, which will be found on examination, after removal, to be charged with negative electricity.

Charged conductors with points attached to them become rapidly discharged by the escape of electricity from the point. When points connected with the earth are presented to charged bodies, the bodies become rapidly neutralized by the escape of the opposite electricity from the point to them.

Fig. 340.



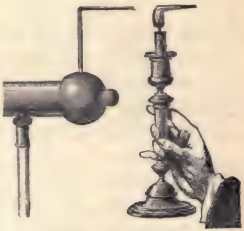
386. *Electrical Machine.* — A common form of an electrical machine is shown in Figure 340. It has a circular glass plate, which turns on an axis supported by two wooden uprights. The plate turns between two pairs of cushions, one above and the other below its axis. In front of the plate are two metallic conductors supported on glass legs. An arm studded with metallic points directed towards the front of the plate is connected with each of

these conductors. The plate becomes charged with positive electricity by friction as it turns between the cushions, and acts upon the points by induction. Negative electricity escapes from the points to the plate, neutralizing the positive electricity, while positive electricity accumulates on the conductors. The cushions are connected with the earth to allow the negative electricity developed on them to pass off. To avoid loss of electricity from the portion of the plate which is passing from the cushions to the points, it is covered with sectors of oiled silk on both sides.

Every electrical machine may be considered as a kind of electrical pump for raising electricity to a higher potential. With the frictional machine only a small quantity of electricity is developed, but it is raised to an enormously high potential.

387. *The Electric Wind.* — The electricity which escapes from a point charges the molecules of air in front of it, which are then repelled by the point. As new molecules come in to take the place of these, they are again charged and repelled. In this way a current of air is made to set off from the point, which may be felt by the hand or be made to flare the flame of a candle if the point is connected with the conductor of an electrical machine (Figure 341).

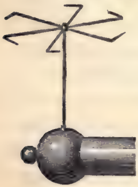
Fig. 341.



388. *The Electric Mill.* — The *electric mill* (Figure 342) consists of a set of metallic arms which radiate horizontally from a centre which is poised upon a point so as to turn freely. The arms are pointed at the ends and all bent around in the same direction. When the mill is

connected with the conductor of an electrical machine in action, the arms revolve in a direction opposite to that in which their ends point. The motion of the mill is due to the reaction of the molecules of the air upon the points. The electric force acts as a stress of repulsion between the molecules and the points, pushing them in opposite directions.

Fig. 342.



F. Electrical Condensation.

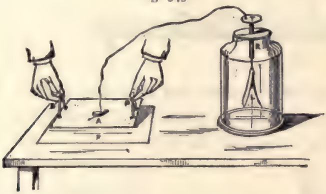
389. *Electrical Capacity.* — The electrical capacity of a conductor is measured by the amount of electricity required to charge it to a unit of potential. The higher the potential to which a given amount of electricity will charge a conductor, the less its electrical capacity.

390. *The Capacity of a Conductor increases with the Extent of its Surface.* — Suspend a large and a small tea-canister by silk cords, and charge equally two metallic balls of the same size and hung on silk threads, by bringing them both in contact with the conductor of an electrical machine and then with each other. Lower one of the balls into each of the canisters so as to touch it. Test each of the canisters with an electrometer. The smaller canister will be found to have the higher potential, and as each received exactly the same amount of electricity, it must have the smaller capacity.

391. *The Capacity of a Conductor increases with its Facilities for Induction.* — Place a sheet of tin-foil upon the top of a dry glass plate provided with insulating handles, and connect the foil to the gold-leaf electroscope by means of a fine wire, which may be held to the foil by a small weight, as shown in Figure 343. The sheet of foil should be somewhat smaller than the plate. Rest the glass plate and

foil on an insulating stand so as to separate it a foot or so from the table. Place a second sheet of tin-foil or of tin on the table at the foot of the stand. Transfer enough electricity to the tin-foil upon the glass plate, by rubbing the little weight on it carefully with an excited tube, to cause the gold leaves to diverge strongly. Take the glass plate by its insulating handles and lower it upon the tin-foil on the table. The gold leaves will partially collapse. Raise the glass plate again, and the gold leaves will diverge. Now as the tin-foil on the glass plate has the same amount of electricity on it all the time, its capacity must increase

Fig. 343.



as it comes nearer the tin-foil on the table, since its potential then falls. As it comes nearer the tin-foil on the table, its facilities for induction increase.

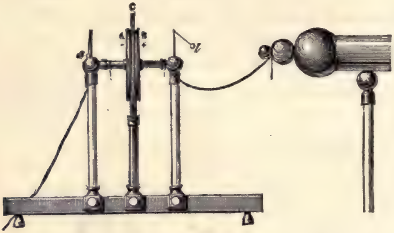
The facilities of a conductor for induction increase with the thinness of the insulator which separates it from neighboring conductors, and with the specific inductive capacity of the insulator.

392. *Electrical Condensation.* — The lowering of the potential of a charge by increasing the conductor's facilities for induction is called *electrical condensation.* The greater the condensing power, the greater the capacity of a conductor. An instrument for increasing the capacity of a conductor by condensation is called an electrical *condenser*, or *accumulator.*

393. *The Action of Condensers.* — The action of con-

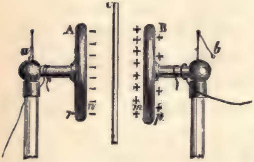
densers is illustrated in Figures 344 and 345. The metallic plates *A* and *B* are separated by a thin plate of glass, *C*. *B* is connected with the conductor of an electrical

Fig. 344.



machine, and *A* is connected with the earth. As positive electricity passes to the plate *B*, it acts upon *A* by induction, drawing negative electricity next to the glass, and repelling positive electricity to the earth. This negative electricity tends to draw the positive electricity of *B* to the side *m* next to the glass and to hold it there; a part of the electricity of *B*, however, remains on the side *p*. As electricity passes to *B* from the machine the accumulation of positive and negative electricities on *m* and *n* goes on increasing, and also the amount of electricity on *p*. This will continue till the potential of *p* is equal to that of the conductor of the machine. The condenser has then received its maximum charge from the source of electricity. The electricities on *m* and *n* are *fixed* by their mutual attractions, while that on *p* is *free*.

Fig. 345.



The capacity of the condenser increases with the size of

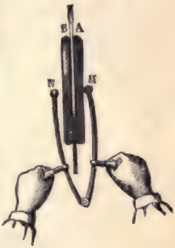
its metallic plates and with its inductive power. The inductive power increases with the thinness of the insulating plate *C*, and with its specific inductive capacity.

The insulating plate is in a state of strain, and if it be made too thin, the stress upon it is so great that it breaks under the strain and the electricities rush together through it.

Owing to the strong attraction of the electricities on the opposite sides of the insulator for each other, a condenser will retain its charge a long time.

Disconnect *A* from the earth, and *B* from the machine. Touch *A* with the finger, and no electricity will escape from it, for all the electricity on *A* is fixed on the side next the glass. Remove the finger from *A* and touch *B*. The free electricity on *p* escapes from *B* and the ball at *b* falls. The escape of a part of the electricity from *B* releases a part of the negative electricity on *n*, which becomes free. Consequently the ball *a* rises. Remove the finger from *B* and touch *A*. Its free electricity will escape, *a* will fall, a part of the positive electricity will be set free, and *b* will rise. By touching each plate alternately the condenser will be gradually discharged. If a bent metallic rod be brought in contact with both *A* and *B* at the same time (Figure 346), the condenser will be suddenly discharged through the rod.

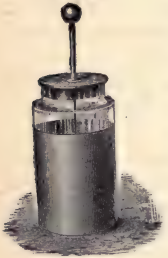
Fig. 346.



394. *The Leyden Jar.* — The *Leyden jar* is an electrical condenser. In its common form it consists of a wide-mouthed bottle of hard white glass (Figure 347), coated inside and out with tin-foil. The tin-foil stops a few inches from the mouth of the bottle. The bottle is closed with a lid of hard wood, in the centre of which

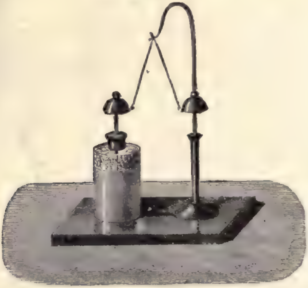
is a brass rod with a ball at its top. A chain hangs from the lower end of the brass rod and touches the inside tin-foil.

Fig. 347.



The inside foil can be charged with positive electricity by placing the ball near the positive pole of an electrical machine, and working the machine as long as the sparks will pass. When sparks refuse to pass, the inner foil is charged almost to the potential of the pole of the machine. This positive charge acts inductively through the glass, and induces a negative charge on the inside of the outer tin-foil, and a positive charge on its outside. If the outer tin-foil is connected to earth, the positive electricity is driven off into the earth, while the negative electricity is held next to the glass.

Fig. 348.



The jar may be gradually discharged by alternate contacts, as in the preceding case, by an arrangement shown in Figure 348. The rod connected with the inner coating has a bell upon the top of it, while a second bell on a

metallic rod is connected with the outer coating by means of a strip of tin-foil on the base. A small metallic ball is hung between the bells on a silk thread. The ball is first attracted by the positive bell, and becomes charged with positive electricity. It is then repelled to the other bell, which has become negative by the release of some of the negative electricity on the outer tin-foil, owing to the removal of some of the positive electricity from the inner tin coating of the jar. It gives up its positive electricity to this bell, and is then again attracted to the positive bell.

The jar may be suddenly discharged by means of a discharging rod, as shown in Figure 349. The outside coating is touched with one end of the discharging rod, while the other end is brought near the ball. There are now two strains going on; one is the strain of the glass which is constant, and the other is the strain of the air between the ball and discharging rod, which increases as they come nearer together.

Fig. 349.

At last a point is reached when the air is no longer able to resist the straining force, and the electricities burst through it and combine with a flash and a report. Immediately after this has occurred, the jar is found to be completely discharged.

After a short time, however, the jar will be found to have acquired again a small charge. This second charge is called the *residual* charge.

"The phenomena of residual charge can be explained only by supposing the induction passing through the glass to be a state of strain of the particles of the glass. On this hypothesis we suppose the glass in the charged jar to be very much strained,

but not to be perfectly elastic. On the tin-foils being discharged — that is, on the removal of the straining force — the particles of glass instantly fly back almost, *but not quite*, to their normal unstrained position. For a moment we then have the tin-foils discharged, but the glass in a slightly strained state. In the course of a few minutes the glass slowly recovers from this residual strain.

"Thus, while the inner tin-foil has remained insulated, a change has occurred in the electrical arrangement of the particles of glass near it. *The state of strain has altered.*

"Now in the ordinary phenomena of induction, the effect of altering the state of strain of an insulator (by bringing a charged body near it) is to induce a charge on any adjoining conductor.

"In the present case the residual charge is produced by the change from a more to a less strained state, which takes place in the glass by virtue of its elasticity.

"A further proof that the phenomena of the Leyden jar are the effects of strain is found in the fact that *any* mechanical agitation of the particles of the glass, which enables them to move more freely over one another, hastens the development of the residual charge."

395. *Large Condensers.* — Sometimes a condenser of very large surface is formed by placing a great number of alternate plates of insulator and tin-foil together. In this case the 1st, 3d, 5th, etc. tin-foils are connected together, and correspond to one coating of the Leyden jar, and the 2d, 4th, 6th, etc. are connected and correspond to the other. The insulator in these large condensers is sometimes mica and sometimes paper which has been dipped in melted paraffine wax.

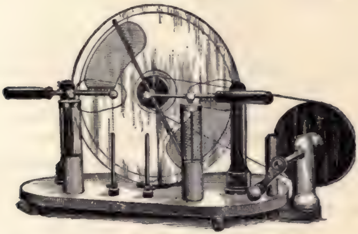
Messrs. Clark and Muirhead's great condenser, which has been constructed for "duplexing" the direct United States cable, contains 100,000 square feet, or more than 2 acres of tin-foil, and fills 70 boxes each 2 feet long, 1½ feet wide, and 7 inches deep.

By means of these condensers large charges of electricity may be obtained from sources of low potential.

G. Electrical Discharge.

396. *Holtz's Electrical Machine.* — Holtz's electrical machine is one of the most powerful machines ever yet invented for obtaining electricity of high potential. In its simplest form it consists of two rather thin discs of glass placed near together in a vertical position, as shown in Figure 350. One of these discs is capable of turning rapidly on a horizontal axis which passes through a hole in the centre of the other disc, which is stationary. The

Fig. 350.



rotating disc is a little smaller than the other and has no openings in it. There are two apertures, called *windows*, in the stationary disc at the ends of a horizontal diameter. Just above one of these windows and below the other, there is a paper sector fixed upon the disc. Blunt tongues of paper run from each sector through the window so as to touch lightly the rotating disc. We will call the stationary disc the back of the machine and the rotating disc the front. In front of the rotating disc there is a metallic comb with its points towards the disc and just in front of the tongues from the paper sectors. These combs are connected with the discharging rods, which constitute the poles of the machine. Under each discharging rod is a small condenser.

On beginning to use the machine, it is necessary to charge the two paper sectors, one with positive and the other with negative electricity.

"One of the sectors is usually charged with negative electricity by induction or friction. The discharging rods are brought in contact, as shown in Figure 351. Suppose the sector *A* (placed a little one side for convenience of representation) charged with negative electricity. It will act inductively through the rotating disc upon the points *A'*, and draw positive electricity out of them upon the glass, and drive negative electricity to the points *B'*.

Fig. 351.

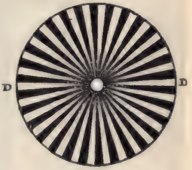
This electricity will act inductively upon the sector *B b*, charging its base *B* with positive electricity and its point *b* with negative electricity. The negative electricity will escape from the points *B'* and *b* to the front and rear surfaces of the rotating disc. The disc is turned in the direction of the arrows, or against the tongues from the sectors. As the disc passes *b* and *B'* in its first revolution, both its front and rear surfaces will become charged with negative electricity. As these negative electricities come round to *a*, they act inductively upon the sector *A a*, and upon the points *A'*. They charge the point *a* of the sector with positive electricity, and increase the negative charge on the base *A*. The sector *B*, the sector *A* with its increased charge and both surfaces of the disc now act inductively upon the points *A'* so as to tend to cause positive electricity to escape from them. Hence more than enough electricity to neutralize the front surface of the rotating disc will escape from these points to the disc. Also both surfaces of the rotating disc as they come to *a*, and the positive electricity which escapes from *A'* will act inductively upon *a* so as to cause positive electricity to escape from it. Hence more than enough electricity will escape from it to neutralize the negative electricity on the rear surface of the rotating disc. Hence, as the disc

passes the point A' and a, both its front and rear surfaces become charged with positive electricity. As these positive electricities come round to b, they act inductively upon the sector $B\ b$ and the points B' in such a way as to increase the positive charge at B, and as to cause more than enough negative electricity to escape from the points b and B' to neutralize the positive electricities on the surfaces of the disc. Hence, as the disc passes the points b and B', both its surfaces become again charged with negative electricity. Thus, both the surfaces of the disc above will be all the time charged with negative, and below with positive electricity. As the disc is rotated, the charge on the sectors A and B increases till it reaches a maximum which cannot be passed.

397. *Spark Discharge.* — On separating the discharging rods of a Holtz machine, and rotating the disc rapidly, a torrent of sparks will pass between the rods. These sparks are due to the passage of electricity through the air between them. The spark is the ordinary form of electrical discharge through dry gases of the ordinary density.

The spark is of very short duration. It lasts less than one thousandth of a second. The spark is very brilliant, and the impression of its light lasts much longer than the spark itself. The short duration of the spark may be shown by the following experiment. A disc (Figure 352) divided into a number of sectors alternately black and white is put into rapid rotation. The colors of the sectors blend in the eye so that the sectors become utterly undistinguishable, and the disc appears of a uniform gray. If the rotating disc is placed in a darkened room so as to be illuminated by a succession of electric sparks, each sector becomes perfectly distinct, and the disc appears to be standing still. The disc is visible only while the light of the spark is upon it,

Fig. 352.



and the duration of the light is so short that the disc does not have time to turn an appreciable amount while the light is on it.

The light of the spark is due to the fact that the line of air through which the electricity passes is heated white-hot by the electric discharge. The sound of the spark is due to the sudden expansion and contraction of this heated line of air.

Fig. 353.

When the spark is short it is usually straight. When it is long, the spark becomes zigzag and branching, as shown in Figure 353.

Fig. 354.

398. *The Spangled Pane.* — If a number of pieces of tin-foil are arranged on a plate of glass a little way apart, and an electric discharge is allowed to pass through them, sparks will be obtained at every interval between the pieces of foil where the electricity is obliged to pass through the air.

Very pretty effects may be obtained by pasting a long strip of tin-foil on a pane of glass in parallel lines connected at alter-

nate ends, between a knob at the top and at the bottom of the pane (Figure 354), and then tracing a design on the pane by means of a sharp point, which cuts through the strips of tin-foil wherever the lines of the pattern cross them. If a discharge is allowed to pass between the knobs, the design comes out in light, a spark being produced wherever a strip of tin-foil is cut through. Such a pane of glass is called a *spangled pane*. When the two knobs of the pane are connected to the two discharging rods of a Holtz machine in action, the effect is very pleasing. The rod or wire from one of the knobs should not quite touch the discharging rod of the machine. An interval of half an inch should be left for sparks to pass.

399. *Auroral Discharge.* — An *auroral tube* is a long tube of glass, of an inch and a half or two inches internal diameter, closed at the ends with brass caps through which pass metallic rods terminating within the tube and near its ends in small brass balls or points. One of the caps is fitted with a stop-cock for exhaustion of the air from the interior. If this tube is screwed to the plate of an air-pump, and the caps are connected with the discharging rods of a Holtz machine, it will be found, on putting the machine in action and working the air-pump at the same time, that a longer spark can be obtained in a partial vacuum than in air of the ordinary density. It will also be found that the appearance of the discharge changes as the exhaustion proceeds. The light becomes softer and more diffused until finally the whole tube is filled with a pale light. At the same time the noise of the spark is diminished till the discharge becomes inaudible.

This form of discharge, which is common to all highly rarefied gases, is called the *auroral discharge*, or the *vacuum discharge*. The color of the light in this discharge changes with the gas used.

Tubes containing various gases in a highly rarefied state

are often prepared and sealed up so as to be ready for use without the trouble of exhaustion. These tubes are called *Geissler's tubes*, or *vacuum tubes*.

The light of the auroral discharge has great power of exciting fluorescence. Hence, if any portion of the glass of the tube is colored with a fluorescent substance, as uranium, or any portion of the tube passes through a fluorescent liquid, as a solution of sulphate of quinine, when the discharge takes place, the uranium glass glows with a soft green light, and the sulphate of quinine with a soft blue, each becoming fluorescent. The accompanying plate represents a vacuum tube. The spiral portion near each end passes through a solution of sulphate of quinine contained in a wider external tube. The green portions are colored with uranium.

The red shows the natural color of the discharge in rarefied air. The sulphate of quinine is quite colorless by ordinary daylight, and the uranium very nearly so.

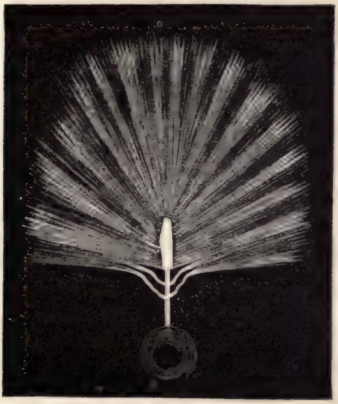
400. *The Glow Discharge.* — When a metallic point is attached to the conductor of an electrical machine in action, it will be seen in the dark to be covered with a soft glow of light. We have seen that in this case a stream of molecules of air sets off from the point, and that these molecules carry electricity away with them, and so discharge the conductor. This discharge is called *convective discharge*. The surfaces between which convective discharge is taking place are covered with a faint glow of light. Hence convective discharge is often called *glow discharge*. In spark discharge the electricity leaps from molecule to molecule through the intervening air, while in convective discharge the electricity is carried along by the molecules which traverse the intervening space.

401. *Brush Discharge.* — Remove the condenser from under the discharging rods of a Holtz machine, put the machine in action, and separate the rods. Instead of the

ordinary spark discharge we shall find the space between the rods filled with a pale, diffused purplish light. From the form of this light, this discharge has been called the *brush discharge.*

The brush discharge seems to be a blending of the spark and the convective discharge. The electricity is some of the time carried by the molecules of the air, and some

Fig. 355.



of the time it leaps along from molecule to molecule. In a darkened room brushes of light will be seen on various parts of a powerful Holtz machine in action. The brush sometimes assumes the form shown in Figure 355.

II.

VOLTAIC ELECTRICITY.

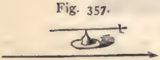
A. Deflection of the Needle.

402. *The Electric Current.* — The flow of electricity through a conductor is called the *electric current.* The phenomena of electricity in motion, or of current electricity, are usually classed together under the head of *voltaic electricity*, to distinguish them from those of electricity at rest, or of *frictional electricity.* The former department of electricity is sometimes called *dynamical electricity, electro-dynamics*, or *electro-kinetics;* and the latter, *statical electricity*, or *electro-statics.* The term electro-kinetics, which is the more modern term, is from two Greek words meaning electricity and motion.

403. *Action of Current on Magnetic Needle.* — Oersted discovered, in 1819, that a current flowing through a wire near a magnetic needle, which is poised so as to turn freely in any direction, would deflect the needle. If the wire is held over the needle (Figure 356), the needle will be deflected in one direction. If the same wire is held under the needle (Figure 357), the needle will be deflected in the opposite direction. If the current is made to flow in the opposite direction through the wire while over or under the needle, the needle will be deflected in the opposite direction to what it was before.

Fig. 356.

Fig. 357.



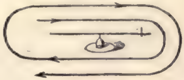
If two currents flow, one over the needle in one direction, and one under the needle in the opposite direction, they will both tend to turn the needle the same way. In any case, the stronger the current the greater the deflection of the needle.

If the wire conveying it is bent round the needle, as

in Figure 358, the current will flow in opposite directions above and below the needle. Hence both portions of the current will tend to turn the needle the same way, and the deflection will be greater than when the current flowed simply over or under the needle. If the wire is carried a sec-

Fig. 358.

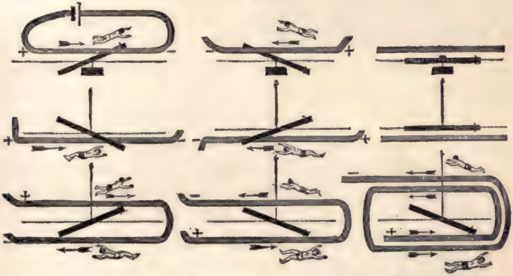
Fig. 359.



ond time around the needle (Figure 359), the deflection of the needle will be increased, since there will now be two currents above the needle and two below it, all tending to turn the needle the same way.

404. *Ampère's Rule.* — Ampère has given the following rule for ascertaining the direction of the deflection of the

Fig. 360.



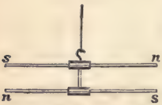
needle in any case: Imagine a little swimmer in the electric current, always swimming with the current, and with his face to the needle. The north pole of the needle will always be deflected to his left (Figure 360).

405. *Simple Galvanometer.* — A *galvanometer* is an instrument for showing the presence, direction, and strength of an electrical current. A simple galvanometer consists

of a magnetic needle, free to turn in a horizontal or vertical plane, and surrounded with a coil of wire. This galvanometer shows the presence of a current in the wire with which it is connected, by the deflection of the needle; the direction of the current, by the direction in which the needle is deflected; and the strength of the current, by the amount of the deflection.

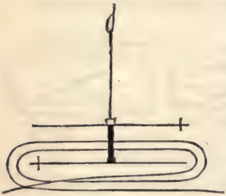
406. *Astatic Needle.* — The directive action of the earth upon a magnetic needle impedes its deflection by the current. This directive action may be neutralized by combining two needles, as shown in Figure 361. The needles are fastened together rigidly at the centre; and the poles of one needle are the reverse of those of the other. As there is a north and a south pole at each end of the combination, each needle must neutralize the directive action of the earth upon the other. Such a combination of needles is called an *astatic needle* (unsteady needle).

Fig. 361.



407. *Astatic Galvanometer.* — An *astatic galvanometer* is one in which an astatic needle is used. The two needles of the combination are almost, but not quite, of the same strength. The needles are hung on a fibre of silk, and the wire is coiled around the lower needle (Figure 362). It will be seen by Ampère's rule that the current that flows between the needles will tend to turn both needles the same way, while that which flows under the lower needle will tend to turn the needles in opposite directions. Owing to the greater distance, its action on the upper needle will be much feebler than its action on the lower needle. Such a

Fig. 362.

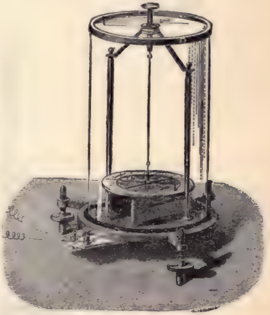


galvanometer is very sensitive, since the directive action of the earth is nearly neutralized, while the effective action of the current is increased by the use of two needles.

When it is desired to make this galvanometer extremely sensitive, the needles are made very light, and are hung on

Fig. 363.

Fig. 364.



a single fibre of silk, and the wire is coiled several thousand times around the lower needle. In this case the wire is very fine, and is wound on a flat reel, of the form shown in Figure 363. The whole is enclosed in a glass case, to protect the needle from currents of air (Figure 364).

408. *Thomson's Reflecting Galvanometer.* — The most sensitive galvanometers ever constructed are Thomson's reflecting galvanometers. These galvanometers are sometimes astatic and sometimes not. In the non-astatic form, one or more magnets, about $\frac{1}{8}$ of an inch in length, are cemented to the back of a light mirror, about $\frac{1}{4}$ of an inch in diameter (Figure 365). The magnets and mirror together weigh less than a grain. They are hung on a single fibre of unspun silk in the centre of a circular coil, which is enclosed in a brass cylinder. The front of this cylinder is of glass.

Fig. 365.

To avoid the inconvenience of always being obliged to place the instrument in the magnetic meridian, a large

Fig. 366.

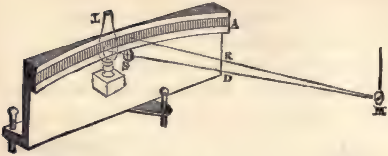
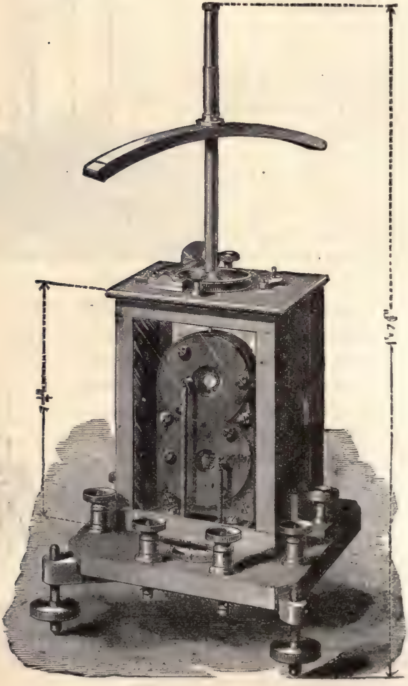


Fig. 367.



curved bar, feebly magnetized, is fixed horizontally on a stem above the case. It turns with friction on this stem, so that it may be placed in any direction. This magnet, by its directive action, forms an artificial magnetic meridian in any desired direction. A scale is placed about a yard in front of the mirror, upon which a beam of light is reflected from the mirror (Figure 366). The movement of the spot of light on the scale magnifies the movement of the needle.

The astatic form of this galvanometer is shown in Figure 367. Each needle is surrounded by its own coil of wire. The current flows through these coils in opposite directions.

409. *Differential Galvanometer.* — A *differential galvanometer* is one which has two coils around the needle, exactly alike in every respect, except that they are wound in opposite directions. The deflection of the needle shows the difference in strength of the two currents, and which is the stronger. When the two currents are equal, the needle is not deflected.

B. Flow of Electricity through Conductors.

410. *Electromotive Force.* — The flow of electricity through a wire connecting two conductors is analogous to the flow of water through a pipe connecting two reservoirs. When the water is at the same level in both reservoirs, no water will flow through the pipe. When the water is at different levels in the two reservoirs, the water will flow through the pipe from the higher level to the lower. The greater the difference between the levels of the water in the two reservoirs, the greater the energy of the current in the pipe. To keep a uniform current in the pipe, the same difference of level must be maintained between the two reservoirs.

In like manner, no current of electricity will flow through a wire connecting two conductors, when the conductors are at the same potential. When the conductors differ in

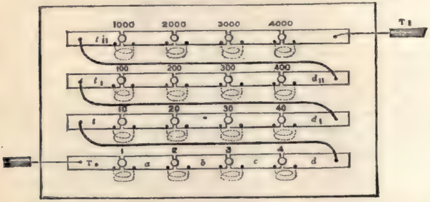
potential, a current will flow through the wire from the higher potential to the lower. The greater the difference of potential between the two conductors, the greater the energy of the current. To keep a uniform current in the wire, the same difference of potential must be maintained between the two conductors.

The force which urges electricity through a conductor is called the *electromotive force.* The electromotive force is always equal to the difference of potential between the points connected by the wire. A certain standard electromotive force has been selected as a unit, and is called a *volt.* A conductor designed to convey a current is called a *circuit.*

411. *Electrical Resistance.* — Every known substance offers some resistance to the passage of the current through it, but different substances differ greatly in the amount of resistance which they offer.

The resistance of a wire varies with its material, its length, and its thickness. The longer and thinner a wire, the greater its resistance. The metals offer comparatively little resistance to the passage of the current, and silver

Fig. 368.



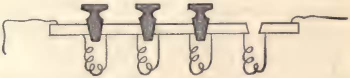
offers the least resistance of all the metals. Copper stands next to silver. The less the resistance any substance offers to the passage of the current, the better conductor it is. A certain standard of resistance has been

chosen as a unit, and is called an *ohm*. It is about the resistance of 250 feet of copper wire $\frac{1}{20}$ of an inch thick.

412. *Resistance Coils and Boxes.* — Coils of wire offering various multiples and submultiples of an ohm of resistance, called *resistance coils*, are arranged in boxes, called *resistance boxes*, in such a way that any amount of resistance may be readily introduced into the circuit.

Figure 368 shows the top of the resistance box. There are several lines of copper plates. The plates in each line are separated from each other by a slight space, and the ends of the plates are shaped so as to furnish a circular aperture for inserting brass plugs between the plates. Under each aperture there is a resistance coil, and the number of ohms of resistance in it is marked beside the aperture on the top of the box. Figure 369

Fig. 369.



shows the resistance coils and the way they are connected with the plates. It will be seen that each coil connects two copper plates in such a way that the current must pass through the coil when the plug is removed from the aperture of a box. When the plug is inserted, the electricity passes through the plug without passing through the coil.

When the resistance box is placed in the circuit, any desired amount of resistance may be introduced into the circuit by removing one or more of the plugs; and the amount of resistance introduced may be ascertained by adding the numbers beside the apertures from which the plugs have been removed.

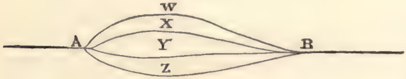
413. *Quantity of the Current.*—By the *quantity* of the current we mean the amount of electricity flowing through the circuit per second. The unit of quantity is the amount of electricity that a volt of electromotive force will cause to flow through an ohm of resistance in a second of time. It is called a *weber*.

The power of a current to deflect a needle is directly

proportional to its quantity. Hence the quantity, or volume, of the current is estimated by its power of deflecting a needle.

414. *Division of the Current.* — When the circuit divides into two or more branches, the current will also divide among the branches in such a way that the quantity of the current in each branch will be inversely proportional to the resistance of the branch. Suppose the circuit divides

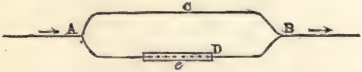
Fig. 370.



at A (Figure 370) into four branches, W, X, Y, Z, whose resistances are in the ratio of 3, 5, 7, and 9. Then $\frac{105}{248}$ of the current will pass through W, $\frac{63}{248}$ through X, $\frac{45}{248}$ through Y, and $\frac{35}{248}$ through Z.

415. *Division of the Current into two Equal Parts.* — In order to have the current divide into two equal parts, it is necessary that the circuit should divide into two branches of equal resistance. If the two branches are not of the same resistance, their resistances may be made equal by introducing a set of resistance coils into the branch which offers the less

Fig. 371.

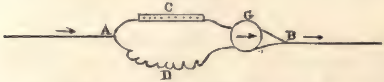


resistance. Suppose the circuit (Figure 371) divides at A into two branches C and D, which reunite at B, and suppose D offers less resistance than C. By employing a resistance box at e we may balance the resistance of C.

416. *Measurement of the Resistance of a Wire by the Equal Division of the Current.* — The equal division of the current between two branches whose resistances are equal affords a ready means of measuring the resistance of a wire. It is only

necessary to make one of the branches *C* (Figure 372), a resistance box, and the other branch *D* the wire to be tested, and to connect each branch with one of the coils of the differential galvanometer *G*. The resistance box must be adjusted until the needle of the galvanometer is not deflected. The currents in

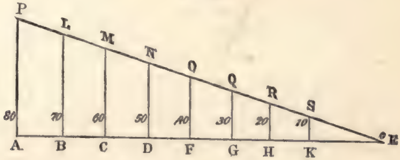
Fig. 372.



the two branches are now equal, and also the resistance of the two branches. The resistance of the branch *C* may be read off from the resistance box, and this is equal to that of the wire *D*.

417. *The Potential of a Wire through which a Uniform Current is flowing.* — Suppose the wire *A E* (Figure 373), to be of uniform resistance throughout, and that a uniform current is flowing through it from *A* to *E*. Its potential will fall at a uniform rate from *A* to *E*. Suppose the potential at *E* to be 0 and at *A* to be 80. Let the perpendicular *A P* represent

Fig. 373.

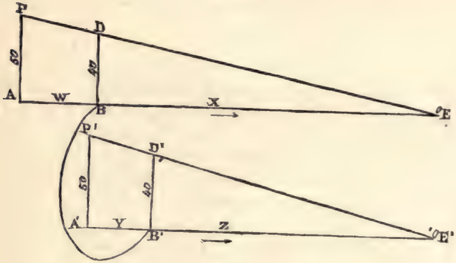


the potential at *A*. *P E* will represent the fall in potential from *A* to *E*. The potential of any point along the wire *A E* will be represented by a perpendicular erected at that point and terminating in the line *P E*. Suppose the points *B*, *C*, *D*, *F*, *G*, *H*, and *K*, to be respectively $\frac{1}{8}$, $\frac{2}{8}$, $\frac{3}{8}$, $\frac{4}{8}$, $\frac{5}{8}$, $\frac{6}{8}$, and $\frac{7}{8}$ of the way from *A* to *E*. Their potential will be represented by the lines *B L*, *C M*, *D N*, *F O*, *G Q*, *H R*, and *K S*, and will be 70, 60, 50, 40, 30, 20, and 10.

In the above cases, the wire being alike throughout, the resistance increases with the distance along the wire. It fol-

lows, therefore, that the potential falls in passing along the wire as the resistance increases. This is true of any wire whatever, whether of uniform resistance or not. That is, if any wire has ten units of resistance, and its potential is 100 at one end and 0 at the other, at one unit of resistance from the first end the potential will be 90 ; at 2 units, 80 ; at 3 units, 70 ; etc.

Fig. 374.



418. *Current in a Wire connecting Two Circuits.* — Let *A E* (Figure 374) represent a wire of uniform resistance throughout, through which a uniform current is flowing from *A* to *E*, whose potential at *E* is 0, and at *A* 50. Let *A P* represent the potential at *A* and *P E* the fall in potential from *A* to *E*. Let *B* be a point ⅕ of the way from *A* to *E*. *B D* will represent its potential, which will be 40.

Let *A′E′* be a second wire of uniform resistance throughout, through which also a uniform current is flowing from *A′* to *E′*. Suppose the potential the same at *A′* as at *A*, and at *E′* as at *E*, and suppose *B′* ⅕ of the way from *A′* to *E′*. The potential of *B′* will be 40.

Suppose *B* and *B′* joined by a wire. No current will flow through this connecting wire, because *B* and *B′* are at the same potential. Connect *B* with any point between *A′* and *B′*, and a current will flow through the connecting wire towards *B*. Connect *B* with any point between *B′* and *E′*, and a current will flow through the connecting wire from *B*.

Let w represent the resistance of AB; x of BE; y of $A'B'$; and z of $B'E'$.

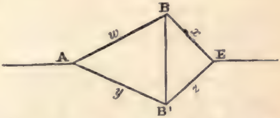
By construction, $AB : BE = A'B' : B'E'$

$$\therefore w : x = y : z.$$

In general, when two wires whose potentials are the same at both ends are connected by a third wire, no current will cross this wire, provided the resistance of the first part of the first wire is to the resistance of its second part, as the resistance of the first part of the second wire is to the resistance of its second part. In every other case a current will cross the connecting wire.

419. *Wheatstone's Bridge.* — The arrangement of the circuit in Figure 375 is called *Wheatstone's Bridge.* The circuit divides at A into two branches, which reunite at E. The points B and B' are connected by a wire called the *bridge.*

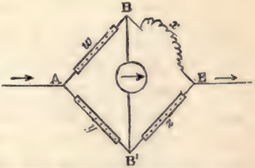
Fig. 375.



Let $w =$ the resistance of AB; $x =$ that of BE; $y =$ that of AB'; and $z =$ that of $B'E$. Since the potentials of both branches are the same at A and also at E, no current will cross the bridge, when $w : x = y : z$. In every other case a current will cross the bridge.

420. *Measurement of Resistance by Wheatstone's Bridge.* — Wheatstone's bridge furnishes a ready means of measuring the resistance of any wire. When used for this purpose the bridge is arranged as shown in Figure 376. Three of the branches, w, y, and z, are made to consist of resistance boxes, and the fourth, x, of the wire whose resistance is to be measured, and a galvanometer is introduced into the bridge. The resistance boxes are then adjusted until the needle of the galvanometer suffers no deflection. As no current is then crossing the bridge, we shall have

Fig. 376.



$w : x = y : z$. The three resistances, w, y, and z, are obtained from the resistance boxes, and x is found by solving the proportion.

421. *The Velocity of the Current.* — A part of the electricity which flows into a wire is used in charging the wire statically. The amount of electricity required for this depends upon the capacity of the wire, and this depends upon its facilities for induction, and this, in turn, upon the nearness of neighboring conductors and the insulating medium which separates it from them. A wire strung on poles some distance above the earth has very small electrical capacity. One nearer the earth has greater capacity, and a submarine cable has a much greater capacity still. In the case of the cable, induction is readily carried on by the wire through its insulating sheath with the water outside. The greater the specific inductive capacity of the insulating sheath, the greater the electrical capacity of the cable.

The velocity of the current in a wire depends upon the resistance of the wire and upon its electrical capacity. The greater either of these, the less the velocity of the current. Hence the velocity of the current varies greatly under different circumstances. It ranges from about 13,000 miles a second to about 60,000 miles a second; or from a velocity which would take it around the earth in two seconds to one which would take it twice around the earth in a second.

C. Electro-Chemical Action.

I. VOLTAIC BATTERIES.

422. *Voltaic Cell.* — If two metal plates *Z* and *C* (Figure 377) are partly immersed in a liquid which acts chemically more powerfully upon one of them than upon the other, and are placed in metallic communication outside of the liquid, either by direct contact or by means of a wire, a current of electricity will flow outside of the liquid from the metal least acted upon by the liquid when alone to the one most acted upon.

When two metals are arranged as above described in a liquid, and are in metallic communication, the one which, if alone, would be least acted on, is entirely protected by the other. The arrangement is called a *voltaic cell*. The portion of the plate least acted on, which is out of the liquid, is called the *positive pole* of the cell, and the corresponding part of the other plate the negative pole.

Fig. 377.

423. *Theory of the Voltaic Cell.* — The voltaic cell is a machine for maintaining a constant difference of potential at its two poles. There are two theories of the action of the cell. Gordon's statement of these theories is as follows: —

"If two metals be placed, near together but not in contact, in a liquid which acts chemically more upon one than upon the other, the metals become charged so that the one least acted on is of higher potential than the one most acted on. The difference of potential produced depends only on the nature of the metals and of the liquid, and not on the size or position of the plates.

"As soon as the difference of potential has reached its constant value, the chemical action ceases.

"If now the metals are connected by a wire outside the liquid, the difference of potential begins to diminish, and an electric current flows through the wire. As soon as the difference of potential becomes less than the maximum for the metals and liquid, chemical action recommences and brings it up to the maximum, and thus, if no disturbing cause interferes, the current will continue till the metal most acted on is entirely dissolved.

"This view of what takes place explains the action very well. It is not yet certain whether this is the true explanation, or whether we should say: On joining two metals either directly

or by a wire, a difference of potential is observed. When the metals, still joined, are partly immersed in a liquid, which acts more upon one than upon the other, the chemical action equalizes the potentials, and in doing so causes a flow of electricity along the connecting wire. The moment the equalization of the potentials has commenced, the difference is renewed again at the point or points of contact between the metals; and so, if no disturbing cause interferes, a continuous flow of electricity is kept up, till the metal most acted on is entirely dissolved.

"The latter view has, in my opinion, more evidence to support it than the former."

When the positive and negative plates outside the liquid are in metallic connection, either by direct contact or by means of a wire, the circuit is said to be *closed;* otherwise the circuit is said to be *open.*

424. *Zinc and Copper Cell.* — In nearly all practical forms of the voltaic cell the negative plate is zinc. The positive plate varies in material.

The simplest form of the voltaic cell consists of a plate of copper and a plate of zinc partly immersed in dilute sulphuric acid, which acts on the zinc, but not on the copper. With such an arrangement the current ceases after a very short time. On examination, the copper will be found to be coated with minute bubbles of hydrogen.

When a piece of zinc alone is dissolved in dilute sulphuric acid (H_2SO_4) it unites with the SO_4, forming sulphate of zinc ($ZnSO_4$), and sets the hydrogen free. When the zinc is dissolved in the voltaic cell, sulphate of zinc is formed, but the hydrogen is liberated, not at the surface of the zinc, but at that of the copper.

When the copper becomes coated with hydrogen, the cell fails to produce a difference of potential and the current stops. Why the hydrogen should appear at the copper, and why it should stop the current, is not well understood.

The zinc of commerce, of which battery plates are made, contains many particles of iron and other metals. If a

piece of ordinary zinc is placed in acid, each of these pieces of iron, together with the zinc near it, forms an independent small cell, whose circuit is always closed whether the main circuit is closed or not. The currents produced in these small circuits in no way help the main current, while they cause the zinc to be rapidly consumed.

The cost of chemically pure zinc prohibits its use, so a different plan is used, which is found to be in every respect equally efficacious with the employment of pure zinc.

It consists in coating the zinc with mercury. This is done by first immersing the zinc for a few minutes in dilute sulphuric or hydrochloric acid, so as to give it a chemically clean surface, and then pouring mercury upon it. The mercury at once combines with its surface, and the whole of the zinc appears bright like silver. Zinc thus "amalgamated" is not attacked by dilute sulphuric acid, unless it forms part of a closed galvanic circuit. The precise action of the mercury is not known.

425. *Smee's Cell.* — In order that a cell may give a uniform current, it is necessary to keep the hydrogen from collecting on the positive plate.

In Smee's cell (Figure 378) the positive plate is platinized

Fig. 378.

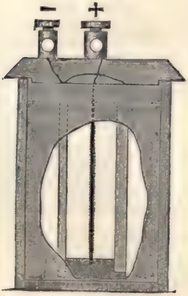
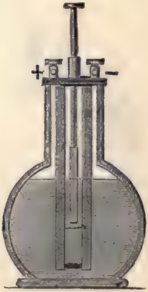


Fig. 379.



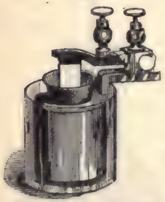
silver, that is, silver with a rough deposit of platinum on its surface, and the negative plate is zinc. The platinum presents a multitude of points, from which the hydrogen disengages itself more readily than from a smooth surface. As the silver is more expensive than zinc, the silver plate is usually placed between two zinc ones, so that both sides of it can be utilized.

426. *Bichromate of Potash Cell.* — In this cell, the plates are of carbon and zinc, and the liquid is dilute sulphuric acid saturated with bichromate of potash. The bichromate absorbs the hydrogen and thus prevents its accumulation on the carbon. One form of this cell is shown in Figure 379. It is so constructed that the zinc plate can be drawn out of the liquid when the cell is not in use. The power of the cell decreases rapidly when in action.

427. *Two-Fluid Cells.* — In all single-fluid cells the compounds formed by the hydrogen in the liquid which absorbs it return to the zinc plate and retard the action on it. Cells with two fluids are designed to prevent this. The two principal types are *Grove's* and *Daniell's* cells. The latter is used when a constant current of moderate strength is required for days, weeks, or months; the former, when a very powerful current is required for a few hours.

428. *Grove's Cell.* — In Grove's cell the metals used are zinc and platinum; and the fluids, strong nitric and dilute sulphuric acids. A cell of thin *porous* earthenware is filled with nitric acid, and contains the platinum plate. This cell (Figure 380) is placed within another cell of glass or vulcanite, containing the zinc and dilute sulphuric acid. The porous earthenware, when wet, permits the electricity to pass freely through it, while it almost entirely prevents the mixing of the liquids. The nitric acid absorbs the hydrogen as fast as it is set free.

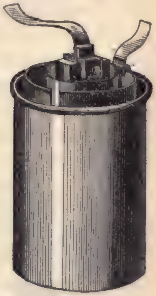
Fig. 380.



429. *Bunsen's Cell.* — Bunsen's cell (Figure 381) is simi-

lar in construction to Grove's, with the exception that the positive plate is carbon instead of platinum. Owing to the impossibility of cutting the coke carbon into thin slices, the Bunsen cell is made larger than Grove's, but it is not so powerful, and is more troublesome and expensive to work.

Fig. 381.



Both Grove's and Bunsen's cells give off fumes of nitrous acid, which are unwholesome, and injurious to instruments. This inconvenience may be obviated by using a solution of bichromate of potash in the porous cup instead of nitric acid. This arrangement is the *two-fluid bichromate of potash cell.* It is much less powerful than either Grove's or Bunsen's, but is extensively used for telegraphic purposes.

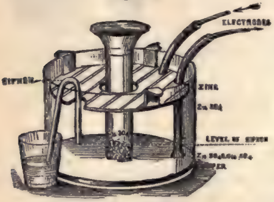
430. *Daniell's Cell.* — In Daniell's cell the plates are zinc and copper. The former is usually immersed in dilute sulphuric acid, and the latter in a saturated solution of sulphate of copper. A convenient form of this cell is shown in Figure 382. The zinc in the form of a rod is placed inside of the porous cell, which is filled with dilute sulphuric acid. The outer cell is filled with the solution of sulphate of copper. It is made of copper, and forms the positive plate of the cell. Inside the copper cell and near the top is a copper shelf perforated with holes, on which are piled a number of crystals of sulphate of copper. When the cell is in action, the hydrogen, as it is set free, is absorbed by

Fig. 382.

the solution of the sulphate of copper which it gradually decomposes. Metallic copper is liberated from this solution and deposited upon the copper, while the zinc is gradually consumed by the sulphuric acid in the porous cup. As the solution of sulphate of copper gets weaker, a fresh portion of the sulphate is dissolved from the shelf. The power of this cell steadily decreases till the dilute acid in the porous cup is saturated with sulphate of zinc, after which it remains constant for a very long time.

431. *Gravity Cells.* — In *gravity cells* the plates are placed horizontally, and the liquids are kept apart chiefly by their difference of density, the denser liquid being placed at the bottom. The best form of this cell, and one which may be taken as the type of all the others, is *Thomson's tray cell* (Figure 383).

Fig. 383.

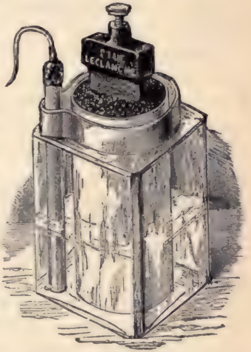


In every form of Daniell's cell the sulphate of copper ultimately finds its way to the zinc and spoils the action. To retard this result indefinitely, Sir William Thomson constructed the tray cell. The copper plate is placed horizontally at the bottom and covered with a saturated solution of sulphate of zinc. The zinc, in the form of a grating, is placed horizontally near the top of the cell. A glass tube is placed vertically in the solution with its lower end just above the surface of the copper plate. Crystals of sulphate of copper are dropped down this tube. These crystals dissolve in the liquid, and form a solution of greater density than that of the sulphate of zinc alone, so that it cannot get at the zinc except by diffusion. To retard this process of diffusion, a siphon, consisting of a glass tube stuffed with cotton wick, is placed with one end midway between the zinc and copper and with the other end in a vessel outside, so that the liquid is very slowly drawn off near the middle of its depth. To supply the place of this liquid, water, or a weak solution of sulphate of

zinc is added above, as required. In this way the greater part of the sulphate of copper, rising through the liquid by diffusion, is drawn off by the siphon before it reaches the zinc, and the zinc is surrounded by a liquid nearly free from sulphate of copper.

432. *Leclanché Cell.* — This cell consists of zinc and carbon separated by a porous cup (Figure 384). The zinc is surrounded by a solution of sal-ammoniac, and the carbon by a mixture of black oxide of manganese and powdered carbon. The cell containing the powder is filled up with water. This cell has small power, but for discontinuous work will remain in action for years, without any other attention than occasionally filling up the cell with water.

Fig. 384.



433. *The Voltaic Battery.* — The *voltaic battery* is a combination of voltaic cells. When the poles of a cell are not connected, they have a certain difference of potential, which is nearly constant for each kind of cell, but varies with the different kinds of cells. When a greater difference of potential is required, it may be obtained by connecting a number of similar cells in *series*, that is, connecting the positive pole of one cell with the negative pole of the next; and so on. All the poles are thus connected two by two, except in the end cells. The free positive and negative poles of these two cells are the positive and negative poles of the battery.

The difference of potential between the poles of the battery is as many times that between the poles of the

cell as there are cells in the battery. In a battery of 4 cells, if we suppose the difference of potential between two poles of the same cell to be represented by the number 10, that between the poles of the battery will be represented by 40; if there are 5 cells, by 50; and so on.

For let us suppose that the negative pole of the end cell is connected to the earth; its potential is zero. The potential of the positive pole will then be 10. But the positive pole of the first cell is in metallic communication with the negative pole of the second, and so their potentials are equal, and therefore the potential of the negative pole of the second cell is 10. But the common difference of potential being 10, the positive pole of the second cell has a potential of 20. This is in metallic communication with the negative pole of the third cell, and therefore the potential of the positive pole of that cell is 30, and that of the positive pole of the fourth cell 40, or the difference between the potentials of the poles of the 4-cell battery is 40, or four times the difference between the poles of each cell.

In electrical diagrams a battery is usually represented by a series of long and thin lines and of short and thick lines. The long line at one end represents the positive pole of the battery; and the short line at the other end, the negative pole (Figure 385).

Fig. 385.

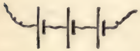
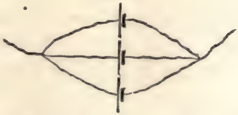


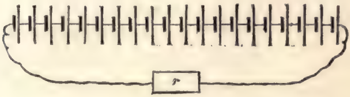
Fig. 386.



434. *Different Ways of arranging the Battery.* — The electromotive force of a battery depends solely upon the number of cells connected in series, and not at all upon the size of the plates. As the electricity has to pass

through the battery as well as through the wire, the battery forms part of the circuit. Now the quantity of electricity which flows through a circuit depends upon both the electromotive force and the resistance. The greater the former and the less the latter, the greater the quantity of the current. The larger the plates of the cell, the less the resistance of the battery. Hence, with the same number of cells in series, the larger the plates the greater the quantity of the current which the battery will give.

Fig. 387.



Instead of using cells with larger plates, the cells are usually connected side by side, as shown in Figure 386. The effect of connecting cells *side* by *side* is not to increase the electromotive force of the battery, but to diminish its resistance, and so to increase the quantity of the current. In Figure 387 twenty cells are represented as connected in series. Both the electromotive force and the resistance of this battery are 20 times those of a single cell of the kind employed in the battery.

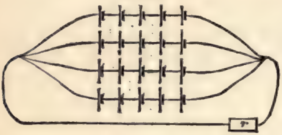
Fig. 388.

In Figure 388, twenty cells are represented as connected side by side. The electromotive force of this battery is that of one cell only, but its resistance is only $\frac{1}{20}$ of that of one cell.

In Figure 389, twenty cells are represented as connected in a way intermediate between the last two cases. First

they are arranged in series of 5 each, forming 4 compound cells, which are connected side by side. The electromotive force of this battery is 5 times that of a single cell, and its resistance is $\frac{5}{4}$ the resistance of a single cell.

Fig. 389.



A battery gives its maximum current when its cells are so connected that its internal resistance is just equal to the external resistance of the wire which connects its poles.

II. ELECTROLYSIS.

435. *Electrolytic Action.* — If two platinum wires, connected with the poles of a battery in action, are immersed in dilute sulphuric acid (H_2SO_4), the acid will be decomposed. The hydrogen will be set free at the wire connected with the negative pole of the battery, while oxygen will appear at the other wire. This action can be most readily shown to a class by placing the dilute acid in a tank with parallel glass sides, and throwing an image of the wires in the tank on a screen. Torrents of bubbles of gas will be seen to rise from the platinum wires. The decomposition of the acid (H_2SO_4) into H_2 and SO_4, and the liberation of these at the two wires is the work of the electric current, and is called the *electrolytic action.* The SO_4 set free at the positive wire attacks the water (H_2O), and, uniting with its hydrogen, forms H_2SO_4, and sets the oxygen free. This latter action is a purely chemical action, and is called the *secondary action.*

If a solution of sulphate of copper ($CuSO_4$) is used instead of the dilute sulphuric acid, copper is deposited on the negative wire, while oxygen is set free at the positive wire. The electrolytic action in this case consists in the

separation of the $CuSO_4$ into Cu and SO_4, and in the liberation of these at the wires. The secondary action is precisely the same as before.

If, in the last case, the wire connected with the positive pole of the battery is copper instead of platinum, no oxygen will be set free, but the wire itself will be gradually eaten away. The electrolytic action is the same as before, but in the secondary action the SO_4 attacks the copper wire instead of the water, and uniting with it forms $CuSO_4$ again, so that the solution will remain of the same strength, while the copper wire is consumed.

436. *Faraday's Nomenclature of Electrolysis.* — Faraday called the decomposition of a substance by means of electricity, *electrolysis;* the substance decomposed, the *electrolyte;* the poles at which the decomposition takes place, the *electrodes;* the one connected with the positive pole of the battery the *anode*, and the one connected with the negative pole of the battery the *cathode;* the products of the decomposition, the *ions;* the one going to the anode the *anion*, and the one going to the cathode the *cation.*

437. *Theory of Electrolysis.* — *Electrolysis occurs only while the body is in the liquid state.* The free mobility of the particles is a necessary condition of electrolysis, for the process can only take place in one of two ways.

The molecule next one of the electrodes is decomposed. One constituent of it goes to the near electrode, and the other *either* travels to the other electrode *or* combines with a constituent of the molecule next to it, setting free a portion similar and equal to itself, which in its turn combines with the corresponding portion of the molecule next to it, and so on. In either case the free mobility of the particles is an essential condition.

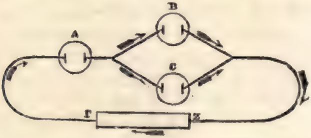
"Clausius, who has bestowed much study on the theory of the molecular agitation of bodies, supposes that the molecules of all bodies are in a state of constant agitation, but that in solid bodies each molecule never passes beyond a certain distance from its original position, whereas in fluids a molecule, after

moving a certain distance from its original position, is just as likely to move still farther from it as to move back again. Hence the molecules of a fluid apparently at rest are continually changing their positions, and passing irregularly from one part of the fluid to another. In a compound fluid he supposes that not only do the compound molecules travel about in this way, but that, in the collisions which occur between the compound molecules, the atoms of which they are composed are often separated and change partners, so that the same individual atom is at one time associated with one atom of the opposite kind and at another time with another.

"This process Clausius supposes to go on in the liquid at all times; but when an electromotive force acts on the liquid, the motions of the molecules, which before were indifferently in all directions, are now influenced by the electromotive force, so that the positively charged molecules have a greater tendency towards the cathode than towards the anode, and the negatively charged molecules have a greater tendency to move in the opposite direction. Hence the molecules of the cation will, during their intervals of freedom, struggle towards the cathode; but will continually be checked in their course by pairing for a time with molecules of the anion, which are also struggling through the crowd, but in the opposite direction."

The same quantity of electricity will always produce the same amount of chemical effect. If three similar vessels, *A*, *B*, *C*, with platinum plates, and containing acidulated water, are ar-

Fig. 390.

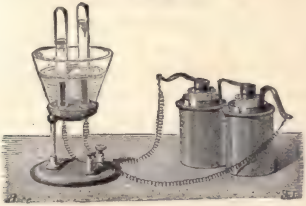


ranged as in Figure 390, and a battery current passes through them, the sum of the quantities of gas produced in *B* and *C* will be exactly equal to that produced in *A*.

438. *The Voltameter.* — The *voltameter* is an instrument

for measuring the quantity of the current. It was invented by Faraday, and consists of a dish filled with acidulated water and fitted with electrodes, as shown in Figure 391. Receivers over the electrodes collect the gases as they are set free. The quantity of the gas liberated per minute measures the mean strength of the current during the time, and the total quantity of the gas collected measures the total quantity of electricity which has passed through the circuit. It is necessary to collect the gases

Fig. 391.



separately, as chemically clean platinum has the power to cause the hydrogen and oxygen to reunite. The receiving tubes are first filled with water and inverted over the electrodes. As the gas rises it displaces the water. The receivers are graduated so as to show the amount of the gas collected.

439. *Electro-Metallurgy.* — Whenever solutions of compounds of metals are decomposed, the metal is deposited upon the cathode. This deposition of metals by means of the electric current is called *electro-metallurgy*. This process is of great practical importance. The two chief processes of electro-metallurgy are *electrotyping* and *electroplating*. The former is copying by means of electricity, and the latter is coating the baser metals with the more noble by means of electricity.

440. *Electrotyping.* — Anything may be electrotyped of

which a mould may be taken in wax. The chief use of electrotyping is in copying the face of printers' type and wood-engravings, after they have been arranged for the pages of a book.

A mould is first taken in wax of the article to be copied. The face of this mould is coated with a thin film of some conducting substance, such as graphite powder. The mould is then hung up in a trough filled with a solution of sulphate of copper, called the *bath*. The mould is connected with the negative pole of the battery, so as to make it a cathode. A plate of copper is hung in the bath opposite the mould, and connected with the positive pole of the battery, so as to make it an anode. On the passage of the current through the bath, copper is deposited from the solution upon the mould in a uniform coherent sheet, while the anode is gradually eaten away by the secondary action. This secondary action keeps the bath of uniform strength. The moulds are usually hung in the bath at night, and in the morning they are removed, and the wax melted off. The copper casts are made sufficiently firm for use in printing by *backing* them with type-metal.

441. *Electroplating.* — The ordinary table-ware, such as knives, forks, tea-sets, etc., is plated with silver by electrolysis. The article to be plated is first very carefully cleaned, and then hung up in a bath containing a solution of cyanide of silver. It is then connected with the negative pole of a battery, while a piece of silver hung in front of it is connected with the positive pole. On the passage of the current, silver is deposited from the solution upon the article which forms the cathode, while the silver of the anode is gradually eaten away by the secondary action. As before, the secondary action keeps the solution of uniform strength. If the article is thoroughly cleaned, and the current is maintained at the right strength, the silver will be deposited uniformly over its surface, and will adhere firmly to it.

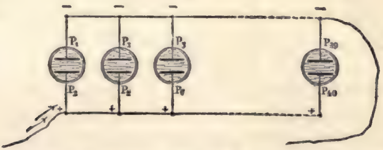
When the article is to be *gilded*, or coated with gold, the bath must contain a solution of the cyanide of gold, and the anode must be of gold. In other respects the process is the same as in silver-plating.

In nickel-plating the bath contains a solution of some compound of nickel, and the anode is a piece of nickel.

442. *Electrolytic Polarization.* — When the battery used is too weak to decompose the electrolyte, a state of ***polarization*** or ***strain*** is set up, which very closely resembles that set up in a Leyden jar. Electrolytic polarization may be compared to the ordinary charging of a Leyden jar, and electrolytic decomposition to the case in which the charge is strong enough to perforate the glass.

443. *Secondary Batteries.* — When a current is sent through a voltameter for a considerable time, the plates acquire some sort of electrical polarization, such that, if the battery is removed and the plates connected by a wire, a current will be observed in the wire in the reverse direction to that of the battery current. When the plates of the voltameter are made very large, it takes a longer time to polarize the plates, but the reversed or "secondary" current is extremely powerful. The secondary current lasts only a short time, but its total energy is equal to the total energy which it has received from the battery in a long time, and therefore, during the time which it lasts, the secondary current will be much stronger than the "primary" or battery current.

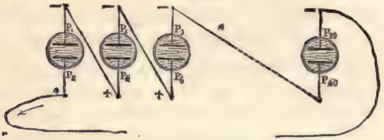
Fig. 392.



Advantage has been taken of this fact in the construction of *secondary batteries*, which enable us with two or three cells of Grove or Bunsen to obtain, for a short time, effects equal to those which could be obtained directly only by the use of many

hundred cells. The plates of these secondary batteries are of lead, and the liquid is dilute sulphuric acid. In order to obtain currents of high potential, a number of secondary elements are

Fig. 393.



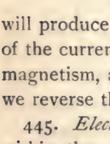
arranged "side by side" and charged, and then are connected "in series." While the elements are being charged they are arranged as in Figure 392.

The connections are then altered to the arrangement of Figure 393, when the differences of potential given to each element separately are all added together, and produce a great difference of potential at the ends of the battery.

D. Electro-Magnetic Induction.

444. *An Electric Whirl constitutes a Magnet.* — If a current of electricity is sent round a wire bent in the form of a ring (Figure 394), the ring will act in all respects like a short magnet. The left-hand side of the ring to a person swimming round it, with the current and with his face towards the centre of the ring, will be a north pole, and the other side of the ring a south pole. If the wire is wound round and round in the form of a coil, the multiplication of the rings will produce a stronger magnet. By changing the strength of the current in such a coil, we change the strength of its magnetism, and by changing the direction of the current we reverse the poles of the magnet.

Fig. 394.



445. *Electro-Magnet.* — If a bar of soft iron is placed within the axis of the coil, and a current sent through the coil, the iron becomes a magnet, with its north pole to

the left hand of a person swimming around the coil with the current and with his face towards the axis of the coil. A wire coiled round a bar of soft iron constitutes an *electro-magnet.*

Such a magnet is active only while the current is passing through its coil. It loses its magnetism the moment the current stops. Its poles are reversed by reversing the current in its coil. As the strength of the current increases the magnetism of the magnet increases, but less and less rapidly, till it reaches a certain point, beyond which an increase in the strength of the current produces no increase of magnetism. At this point the magnet is said to be *saturated.* Below the point of saturation every change in the strength of the current, however slight, produces a corresponding change of magnetism.

Electro-magnets are usually made of the horseshoe form (Figure 395), and they are much stronger than the ordinary steel magnets. The iron core of each coil is often a separate bar, and the two bars are connected by a straight bar at the base.

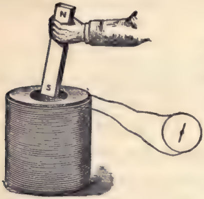
Fig. 395.

446. *Magneto-Electric Currents.* — If a wire is moved in the neighborhood of a magnet in any direction whatever, except along a line of magnetic force, a difference of potential will be produced at the ends of the wire which would cause a current to flow through a wire connecting the ends and not acted on inductively by the magnet. If a person carries a wire in front of him in any direction whatever with reference to the north pole of a magnet, the left-hand end of the wire will be brought to a higher potential. It is the reverse when the wire is moved about the south pole of the magnet.

If a magnetic pole is moved in the neighborhood of a wire, in any direction except parallel to it, a current will

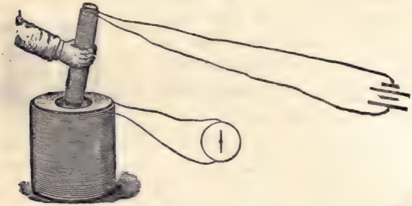
be induced in the wire. If, for instance, a magnet *NS* (Figure 396) is moved suddenly in or out of the coil of wire, a current will be induced in the coil, which will be in one direction on inserting the pole, and in the other on withdrawing it. If the magnet is reversed so as to use the other pole, the current will be reversed.

Fig. 396.



If a coil of wire through which a current is passing is used instead of a steel magnet (Figure 397), precisely similar results are obtained. The more suddenly the steel magnet or the coil conveying a current is moved in or out of the coil, the stronger the current induced.

Fig. 397.

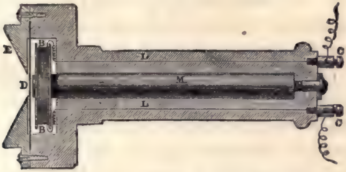


If the small coil is left within the larger coil, any change whatever in the current in the inner coil, whether of strength or direction, will develop a current by induction in the outer coil. So, too, if any two coils of wire, through one of which a current is passing, are near together, any movement of the coils with respect to each other, or any change in the current in the first, will induce a current in the second.

If a bar of soft iron is inserted in the inner coil of Fig-

ure 397, the current induced in the outer coil, either by motion or change of current, will be very much stronger. The same is true to a less extent when a bar of any other metal is inserted in the inner coil.

Fig. 398.



447. *The Bell Telephone.* — Figures 398 and 399 show the sending and receiving instrument of the *Bell telephone*, in section and perspective. It consists of a steel magnet *M* around one end of which is wound a coil of fine wire *B*. The coil and magnet are enclosed in a wooden case, which serves as a handle. One end of this case is considerably larger than the magnet, and is hollowed out at *E*, so as to serve as a mouth-piece or an ear-piece. A diaphragm of thin iron *D* is stretched across the wide end of the case, just in front of the pole of the magnet, which it does not touch.

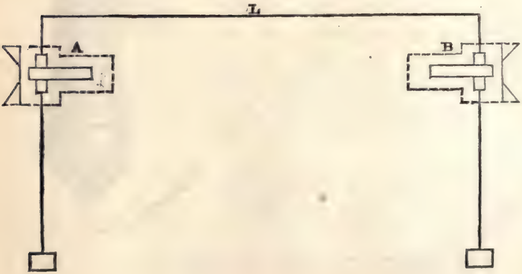
Fig. 399.

The transmitting and receiving instruments, which are exactly alike in construction, are connected together by a wire. On speaking into the mouth-

piece, the air in it is thrown into vibrations, and these vibrations are communicated to the diaphragm. The vibrations of the iron plate produce slight temporary alterations in the magnetism of the steel magnet. These changes of magnetism in the magnet induce corresponding currents in the wire of the coil, which are transmitted over the wire which connects the two instruments. Hence pulsations of electricity exactly corresponding to the vibrations of the diaphragm of the first instrument will be transmitted over the wire and through the coil of the receiving instrument. These pulsations of the current in the coil will induce in the magnet of the receiving instrument exactly the same changes of magnetism as those by which they were produced in the sending instrument. These changes of magnetism cause the magnet to pull upon the iron plate in front of it with a varying force, and, consequently, to make it vibrate exactly like the diaphragm of the transmitter. These vibrations are communicated to the air, and then to the ear of the operator, which is placed at the mouth of the receiver. The words spoken into the transmitter are thus reproduced in the receiver.

Figure 400 shows the way in which the two instruments

Fig. 400.

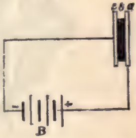


are connected. The wire at each end is connected with the earth by means of a copper plate sunk in the ground, so that the circuit is completed by the earth. Otherwise two wires must be used between the instruments.

The Bell telephone is a beautiful illustration of the two aspects of electro-magnetic induction.

448. *The Edison Telephone.* — In the Bell telephone no battery is used. In the Edison telephone a battery is used, and a current transmitted from the battery is thrown into undulations by an arrangement called the *carbon button.* This button is shown in Figure 401. *b* is a disc or button of carbon, in the form of compressed lampblack; *a* and *c* are metallic plates placed against the front and back of the disc of carbon. One of the poles of the battery *B* is connected with *a*, and the other with *c*. The current is obliged to pass from the plate *a* to *c* through the carbon disc. An increase of pressure upon the metallic plates *a* and *c* diminishes the resistance of the button, either by increasing the density of the carbon disc or by improving the contact between the plates and the disc. The button is exceedingly sensitive to variations of pressure, the slightest alteration of pressure producing a change in the strength of the current which traverses the carbon.

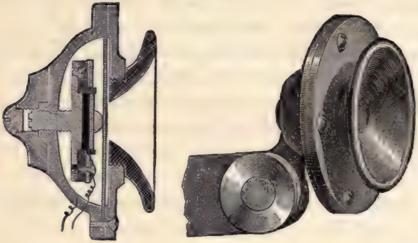
Fig. 401.



One form of the Edison transmitter is shown in Figure 402. The mouth-piece is of vulcanite. Back of this is the vibrating disc, and behind this is a little hemispherical button of aluminium. This button rests upon the metallic plate in front of the carbon disc. This plate is of platinum. Behind the carbon disc is a second platinum plate, held in position by means of the screw at the back of the instrument. The battery wires are connected with the two platinum plates in such a way that the current must traverse the carbon disc.

On speaking into the mouth-piece, the disc is thrown into vibration. These vibrations are communicated to the platinum plate and the carbon disc by means of the aluminium button, thus producing undulations in the current exactly corresponding to the vibrations of the disc at the bottom of the mouth-piece.

Fig. 402.



The receiving instrument of the Edison telephone is similar to that of the Bell telephone. Changes of magnetism are induced in it by the undulating current which traverses its coil, and these changes of magnetism cause the disc in front of the magnet to vibrate exactly like that of the transmitter.

449. *The Induction Coil.* — The *induction coil* consists of two coils: an inner or *primary* coil of coarse wire, enclosing pieces of soft iron, usually in the form of wires; and an outer or *secondary* coil of fine wire. The coils are carefully insulated from each other. A current of electricity is sent through the primary coil, and any change in the strength of this primary current develops by induction a current in the secondary coil. The induced current is much less in quantity than the primary current, but it has a far greater electromotive force.

450. *The Use of the Induction Coil with the Telephone.* —

It has been found that the induced currents from the inductive coil are better adapted for working the telephone than the direct current from the battery. Figure 403 shows the way the coil is used with the telephone. *b* is the carbon disc of the transmitter, *a* and *c* are the platinum plates, *B* is the battery, *d* is the primary coil of the induction coil, and *e e* its secondary coil. The battery is connected with the plates *a* and *c*, and with the primary coil *d*. One end of the wire of the secondary coil is connected with the earth by the wire *G*; and the other end to the line *L*, which runs to the receiving instrument. The undulations of the current in the primary coil induce corresponding undulations of greater electromotive force in the secondary coil. These latter undulations pass over the line, and work the receiving instrument.

Fig. 403.

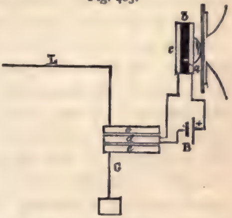
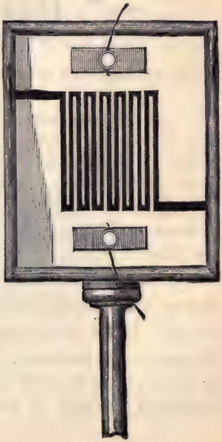


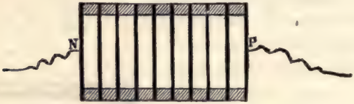
Fig. 404.



451. *The Electrical Receiver of the Photophone.* — It has been found that the conducting power of selenium and certain other substances varies with the intensity of the light to which they are exposed. This suggested to Bell the use of these substances in the receiver of his photophone. In Figure 404 is shown one of the receiving cells employed by Bell. A plate of glass is first coated with silver. The silver is then scratched through in a broad

zigzag line, so as to divide the coating into two portions, as shown in this figure. Interlocking tongues project from the two portions like the teeth of combs. The glass plate is then smoked so as to fill the spaces between the tongues with a good film of lampblack. The two silver combs are connected with the two poles of a voltaic battery. The current is obliged to traverse the film of lampblack in order to pass from one comb to the other. So long as the cell is exposed to light of uniform intensity the current which traverses the cell will be uniform. Any change in the intensity of the light upon the receiver alters the resistance of the lampblack film and the strength of the current. When this cell is used as a receiver, an ordinary telephone receiver is included in the circuit. As in the case of the Edison telephone, the sounds are louder when the cell is in the primary circuit of the induction coil, and the telephone receiver in the secondary circuit.

Fig. 405.



The selenium cell consists of a number of discs of brass separated by thin rings of selenium, as shown in section in Figure 405. The two end discs are connected with the poles of a battery, in the circuit of which is also included a telephone receiver. As before, it is found better to place the selenium cell in the primary circuit of an induction coil, and the telephone receiver in the secondary circuit.

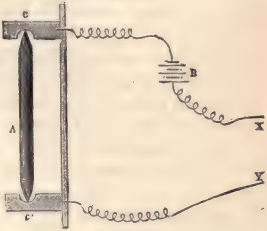
When the selenium cell is used as a receiver, it is placed in the focus of a parabolic or cylindrical mirror.

452. *The Microphone.*—When there is an imperfect contact at any point of a circuit carrying a battery current, any change in the goodness of the contact will produce a change in the strength of the current, and cause a sound in a telephone receiver included in the circuit. When the imperfect contact is between pieces of carbon lightly

pressed together, variations of the current are produced by the slightest sounds occurring near the carbons.

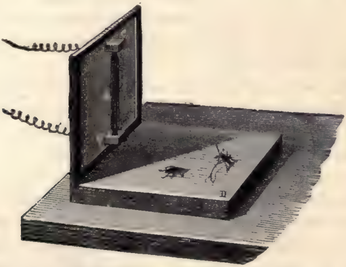
The microphone consists of three pieces of carbon, *C*, *A*, and *C′* (Figure 406). The wires from the battery *B* are connected with the pieces *C* and *C′* in such a way that all the pieces of carbon are in the circuit. The wires *X* and *Y* run to the receiver of a telephone. The lowest whisper spoken near the microphone is loudly reproduced in the telephone. As the carbon rod *A* is thrown into vibrations by the pulsations of sound, it alternately lengthens and shortens. These alterations of length alternately improve and impair the contact at *C* and *C′*.

Fig. 406.



To intensify the effect, the microphone is usually placed on a sounding-board *D* (Figure 407). The sound caused by a fly walking on the sounding-board is distinctly audible at the distant telephone. The ticking of a watch on the sounding-board sounds like the blows of a hammer.

Fig. 407.



453. *The Audiometer.* — This instrument is shown in Figure 408. B and C are two coils of wire, exactly alike, and placed at opposite ends of a rod divided into inches and fractions of an inch. D is a coil that may be slid along this rod, E is a microphone, and F is a battery. The battery is connected with the microphone, and with the coils B and C in such a way that the current traverses them in opposite directions. The sliding coil D is connected with a telephone receiver. A watch is placed upon the microphone, which must be in a distant room, so that the ticking of the watch cannot be heard directly. The undulations in the current produced by the microphone, as they traverse the coils B and C, induce similar undulations in the coil D, but the undulations induced by B will be in opposite directions to those induced by C. When the coil D is at the centre of the rod, the two sets of undulations induced in it will be equal and will neutralize each other, and no sound will be heard at the telephone. As D is moved away from the centre, one set of induced undulations will begin to exceed the other, and a sound will begin to be produced at the telephone, feeble at first, but becoming more and more intense as D is moved farther and farther from the centre, and reaching a maximum when D is moved up close to either B or C.

The acuteness of one's hearing may be tested by noticing at what point the ticking of the watch becomes inaudible at the telephone as D is moved slowly towards the centre of the rod. On testing both ears in succession, it will often be found that one ear hears better than the other.

454. *The Induction Balance.* — The induction balance (Figure 409) differs from the audiometer in having two sliding coils instead of one. The end coils G and G' are connected with the microphone and battery as before, and the sliding coils H and H' are connected with the telephone receiver so that the currents from them shall traverse the telephone in opposite directions. The sliding coils H and H' are first placed equally distant from the end coils G and G'. The two induced currents are now exactly balanced, and no sound is heard at the telephone, as the undulations from H exactly neutralize those from H'. If a piece of metal, as a small coin, is slid into one of the end coils, as G, the balance of the induced currents is at once destroyed, and

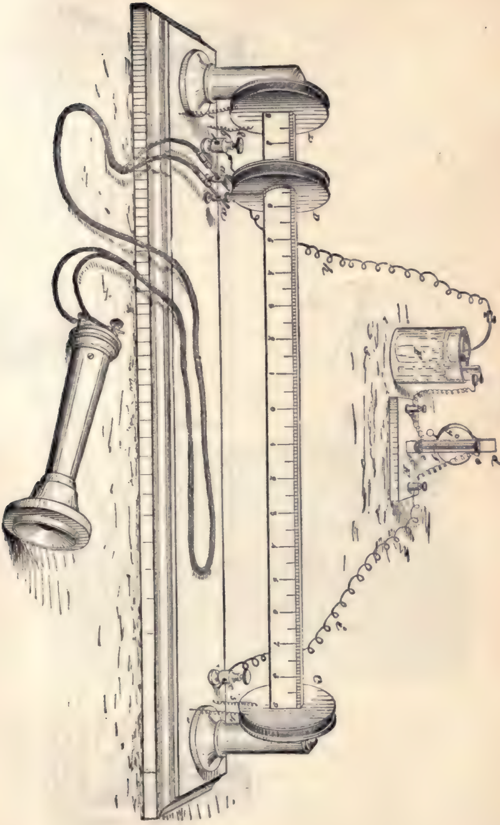


Fig. 408.

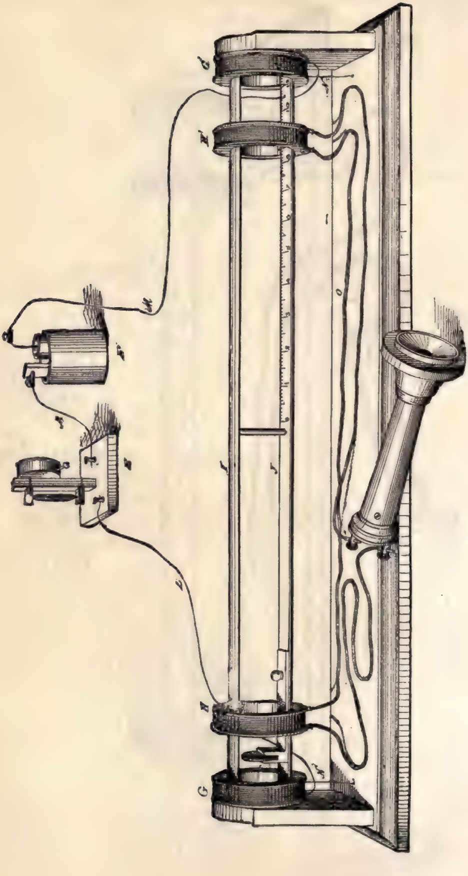


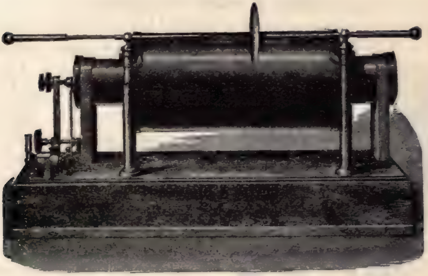
Fig. 409.

the ticking of the watch becomes audible at the telephone. This is because the presence of the metal in the axis of the coil improves the induction of the coil. If two pieces of metal, exactly alike in every respect, are placed in exactly corresponding positions in both the end coils, the balance is again restored, and the ticking of the watch is again inaudible at the telephone. If, however, there is the slightest difference in the weight or purity of the two pieces of metals, the equality of the induced current is again destroyed, and the ticking of the watch is again heard at the telephone.

This instrument may be used for testing the fineness of alloys. An alloy of gold and silver, containing only two ounces of gold to the pound of silver, can be clearly distinguished from pure silver by means of the balance. It may also be used for detecting bad coin.

The telephone, microphone, audiometer, and induction balance furnish the most beautiful and complete illustration of the different aspects of electro-magnetic induction.

Fig. 410.



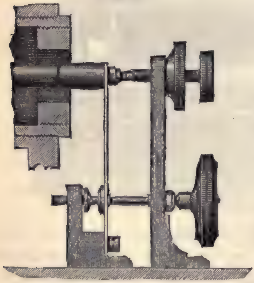
455. *Large Induction Coils.* — Figure 410 shows an induction coil, capable of giving a 17-inch spark in air. Mr. Spottiswoode's great coil (the most powerful ever constructed) is capable of giving a spark in air 42½ inches long. The power of the coil depends in great measure upon the length and fineness of the wire in the secondary coil. In the 17-inch coil the wire in the secondary coil is 22 miles in length, while in the Spottis-

woode coil it is no less than 280 miles long. A good deal also depends upon the quality of the insulation between the primary and secondary coils and between the different layers of the secondary coil. When the current is started or stopped in the primary coil, the sudden change of magnetism in the coil and its iron core produces a great difference of potential at the ends of the wire of the outer coil. The more sudden the change of magnetism, the greater the difference of potential at the ends of the secondary wire. It is found that this difference of potential is greater on stopping the current than on starting it. It would seem that the iron loses its magnetism more quickly than it gains it.

That the destruction of magnetism may be as sudden as possible, it is found necessary to use a bundle of fine wires for the core of the primary coil, instead of a single rod of iron. The wire will lose its magnetism much more quickly than a single rod.

The current is started and stopped by means of what is called a *contact-breaker*. The form of contact-breaker used for small coils (up to 17 inches) is called the *vibrator*. It is shown in Figure 411. It consists of a vertical brass or steel spring, having upon its upper end, in front, a piece of soft iron facing the core of the primary coil, but not quite touching it ; and behind, just opposite the soft iron, a platinum point, which presses against a second platinum point, supported on a vertical post. The wires from the battery are connected with the spring and the rear platinum point in such a way that, when the current passes at all, it must pass from one platinum point to the other. The circuit is closed and the current started when the points are in contact, and it is opened and the current stopped when the points are separated. The elasticity of the spring tends to bring the points together ; but when the cur-

Fig. 411.



rent starts, the core of the primary coil becomes magnetic, attracts the piece of soft iron, and, pulling the spring forward, separates the platinum points, and stops the current. The core then loses its magnetism, the iron is released, and the spring flies back, and brings the platinum points in contact again. The current starts again, the core becomes magnetic, and the points are again drawn apart, and so on.

All the experiments with vacuum tubes succeed better with a large induction coil than with the Holtz machine.

456. *The Extra Current.* — If a current is sent through a *coil* of wire, the current does not instantly reach its maximum value when the circuit is closed, and it does not instantly fall to zero when the circuit is broken. This effect is the same as would be produced if, at the moment of closing, a transient current were produced in the wire in the opposite direction to the primary, and, at the moment of opening, another in the same direction as the primary.

The transient currents in a coil are produced by the induction of each portion of the current on the neighboring wires, on which it acts as if they were portions of another circuit.

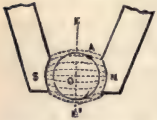
These transient currents are called the *extra currents* of *closing* and *opening*, respectively. If the coil is unwound and stretched out, so that no part is near any other part, except at right angles to it, the extra currents almost entirely disappear. For two wires to act inductively on each other, it is necessary that they should be near together, and not at right angles.

457. *The Condenser of the Induction Coil.* — This is a very important portion of an induction coil. It consists of a number of sheets of tin-foil separated by mica, gutta-percha, or paraffined paper. The 1st, 3d, 5th, 7th, etc. sheets are connected to one end of the primary wire; the 2d, 4th, 6th, 8th, etc., to the other end. When the circuit is broken, the extra current, induced in the primary wire by breaking, is in the same direction as the primary current, and therefore tends to prolong the magnetization of the core. When a condenser is used, the extra current spends itself in charging it. The condenser then, instantly discharging itself, sends a current in the reverse direction round the core, and at once demagnetizes it. The condenser is usually placed in the base of the coil.

458. *Magneto-Electric Machines.* — The fact that electric currents are produced in a wire by any change of magnetism near it, or by moving the wire in the neighborhood of a magnet, has been utilized in the construction of machines for the development of very powerful currents of electricity. These machines are called *magneto-electric* or *dynamo-electric* machines. The former name is applied more especially to the machines in which the electric currents are produced by changes of magnetism, and the latter to those in which the currents are produced mainly by the motion of wire in the neighborhood of magnets. In all the dynamo-electric machines the currents are produced by revolving coils of wire between the poles of powerful horseshoe magnets, which are sometimes steel magnets, but usually electro-magnets.

When a wire is carried around between the poles of a horseshoe magnet, a current is developed in it during each half of a revolution, and these currents will be in opposite directions. Let A (Figure 412) represent the cross-section of a wire moving around between the poles N, S, in the direction indicated by the arrow. When on the right-hand side of the vertical line $E\,E'$, the wire will be crossing the lines of magnetic force in one direction, and when on the left of this vertical, in the opposite direction. According to the rule already given, while the wire is on the right of the vertical line, the back end of it will be at a high potential and the front end of it at a low potential. This will be reversed when the wire is on the left of the vertical line. All modern magneto-electric machines are constructed on one of two types, namely, that of the Gramme machine, and that of the Siemens machine.

Fig. 412.



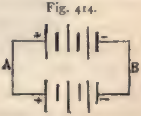
459. *The Gramme Machine.* — The construction of the Gramme machine and the principle of its action may be ex-

plained by means of the diagram given in Figure 413. A ring of soft iron, $M\,N'\,M'\,S'$, is wound with a copper wire, whose ends are soldered together so as to form a continuous conductor. This ring is arranged so that it may be revolved on a horizontal axis between the poles, N, S, of a permanent magnet. The parts of the ring N' and S' are rendered a north and a south pole by induction. As the ring revolves, these poles remain in the same position with reference to the poles N and S of the permanent magnet, but not in the same part of the ring itself. As the ring passes the poles of the permanent magnet, the soft iron becomes magnetized and demagnetized by induction. This

Fig. 413.

change of magnetism in the iron of the ring produces a current in each element of the coil of copper wire in the neighborhood of the change. Also the movement of these elements past the poles of the permanent magnet produces currents in them, and these currents will have the same direction as those produced by the change of magnetism. The currents produced in all the elements of the coil above the line $M\,M'$ will be in one direction and will tend to combine in one current. The currents produced in all the elements of the coil below the line $M\,M'$ will be in the opposite direction to those above the line, and these will also tend to unite in one current. There is then a tendency in the upper half of the ring to produce a current in one direction, and an equal tendency in the lower half of the ring in the opposite direction. The two halves of the coil are now in the condition of two batteries shown in Figure 414. If the points A and B are connected by a wire, a current will flow through the con-

Fig. 414.



necting wire having the electromotive force of either battery and of the quantity of both. In a similar way, if the points of the coil M and M' were connected by a wire, a current would flow through this connecting wire from the point of higher potential to that of lower potential. Whether M or M' be of the higher potential depends upon the direction in which the ring revolves. The points M and M' might be connected by removing the insulating coating from a little strip around the centre of the ring on the outside, and allowing two metallic springs M and M' to press against the denuded portion of the coil as the ring revolves, and connecting these springs with each other by means of a wire.

In the actual construction of the Gramme machine, the iron ring is composed of iron wire, and the copper coil around it is wound in sections, as shown in Figure 415. R R are insulated metallic radial pieces. The ends of the wires of the sectional coils are connected with these radial pieces in such a way that the coils are made to constitute a continuous and endless conductor, as in Figure 414; that is to say, the end of one coil and the beginning of the next are connected to each radial piece. The smaller extensions of the radial pieces, seen at the right, form what is called the *commutator cylinder*.

Fig. 415.

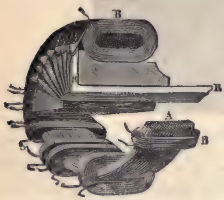
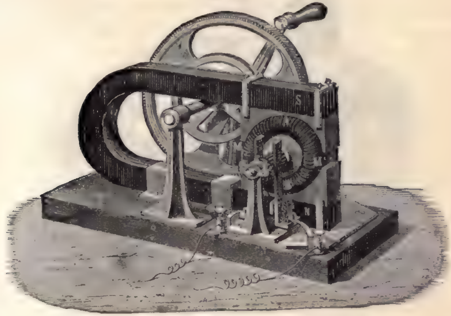


Figure 416 shows one form of the Gramme machine. The poles N and S of the permanent magnet are hollowed out so as nearly to enclose the ring. Metallic brushes at B press against the opposite sides of the commutator cylinder, so as to take off the electricity from the ring at points corresponding to M and M'. This machine is turned by hand by means of the crank. Figure 417 shows a Gramme machine, designed to be driven by steam or water power, in which the steel magnet is replaced by a compound electro-magnet.

460. *The Siemens Machine.* — In the Siemens machine the ring of the Gramme machine is replaced by a cylindrical armature composed of an iron core on which the coil of copper wire is

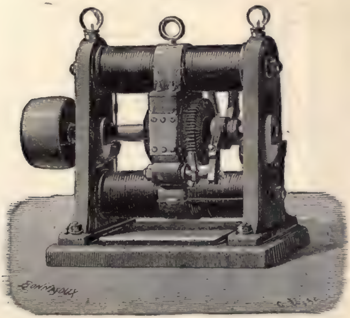
wound longitudinally. One form of this machine is shown in Figure 418. The compound electro-magnet is made wide and

Fig. 416.



flat, so as to give greater length to the armature. The curved portions above and below the cylindrical armature are pieces of soft iron, which constitute the poles of the compound electro-

Fig. 417.



magnet, shaped so as nearly to enclose the armature. The wire on the cylinder is wound in sections, as in the Gramme machine,

Fig. 418.

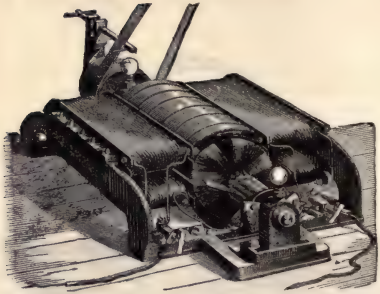
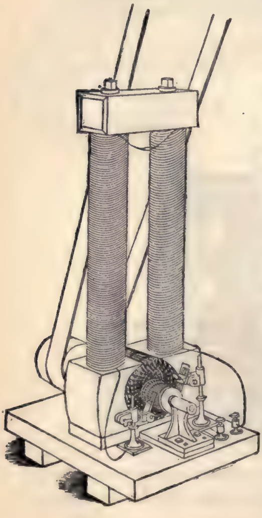


Fig. 419.



and the ends of these sectional coils are connected with insulated metallic strips on the commutator cylinder, so as to form a continuous endless conductor, as in the Gramme machine. The electricity is taken off from these strips by means of metallic brushes. The coils of the electro-magnet are placed in the circuit, so that the current developed by the machine traverses them and develops magnetism. When the machine is started, the current, feeble at first, is developed by means of the residual magnetism of the electro-magnet. This feeble current increases the magnetism of the magnets, and causes a stronger current to be developed, and so on, till the current and magnetism attain their maximum strength.

In the Gramme machine the current is produced chiefly by the change of magnetism; and in the Siemens machine, chiefly by the movement of the wire across the magnetic field.

461. *The Edison Machine.* — The Edison machine is a modification of the Gramme and Siemens machine. It is shown in Figure 419. The armature of this machine, which is shown in section and in perspective in Figures 420 and 421, consists of a core of hard wood, upon which is wound transversely a coil of iron wire, like thread on a spool. Upon this is wound

Fig. 420.

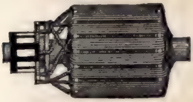


Fig. 421.

longitudinally the coil of copper wire in sections. These sections are connected with insulated metallic plates on the commutator cylinder, so as to form a continuous endless conductor. The electricity is taken off from the commutator by means of metallic brushes.

The iron wire takes the place of the ring in the Gramme machine. The Edison armature is really the Gramme ring and the Siemens armature combined.

E. Telegraphy.

I. THE MORSE SYSTEM.

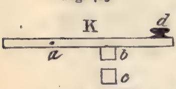
462. *The Principal Instruments of the Simple Morse Tele-*

Fig. 422.

graph.—The principal instruments of the simple Morse telegraph are the *key*, the *relay*, and the *sounder*.

463. *The Key.*—The key is used for opening and closing the circuit. It is shown in Figure 422. Its essential parts are shown in outline in Figure 423. *K* is the lever; *a* is the axis on which it turns; *b* is a platinum point connected with the lever; *c* is a stationary platinum point directly under *b*, called the *anvil;* and *d* is a vulcanite button by which the lever is pressed down. There is a spring under the lever of the key which keeps it up so as to separate the platinum points when the lever is not pressed down.

Fig. 423.



In Figure 424 the key is shown in the circuit of a battery. One pole of the battery is connected with the anvil by a wire, and the other with the lever at the axis. When the lever is up, the circuit is opened at *a* by the separation of the platinum points, and the current is stopped.

Fig. 424.

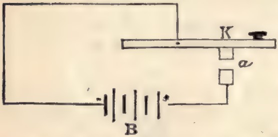
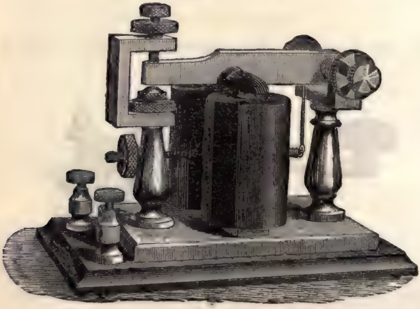


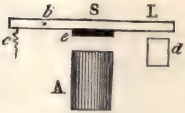
Fig. 425.



When the lever is pressed down, the circuit is closed by the contact of the platinum points at *a*, and the current starts.

464. *The Sounder.* — The sounder is shown in Figure 425. Its essential parts are shown in outline in Figure 426.

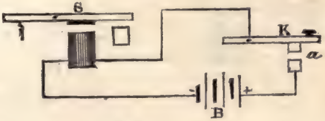
Fig. 426.



A is an electro-magnet; *L* is a lever; *b* is the axis on which the lever turns; *c* is a spring which pulls the lever up; *e* is a piece of soft iron, fastened across the lever just over the electro-magnet; and *d* is a piece of metal against which the lever strikes when it is drawn down.

Figure 427 shows the sounder and key in circuit. One

Fig. 427.



pole of the battery is connected by a wire with the anvil of the key; the other pole is connected with one end of the wire of the electro-magnet of the sounder, and the other end of the wire of this magnet is connected with the lever of the key at the axis. These connections are all made by means of binding-screws on the bases of the instruments.

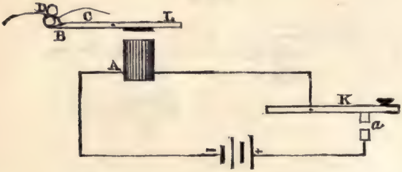
When the lever of the key is up, the circuit is broken at *a*, the current is stopped, the electro-magnet of the sounder is inactive, and the lever of the sounder is thrown up by the spring. If we push the lever of the key down, contact is made at *a*, which closes the circuit; the current starts, the electro-magnet of the sounder becomes active, and the lever of the sounder is drawn down by the pull of

the magnet upon the iron above it. As the lever is drawn down, it clicks because of its striking the metallic stop at the end.

The clicking of the sounder is controlled by the key, even when these are miles apart, for the sounder clicks every time the lever of the key is depressed. Letters and words are indicated by combinations of long and short intervals between the clicks. The operator listens to the sounder just as we listen to one who is talking to us, and soon becomes able to follow it as readily.

465. *The Register.* — Sometimes an instrument called the *register* is used for receiving the message instead of the sounder. The essential parts of this instrument are shown in Figure 428. It resembles the sounder in construction

Fig. 428.

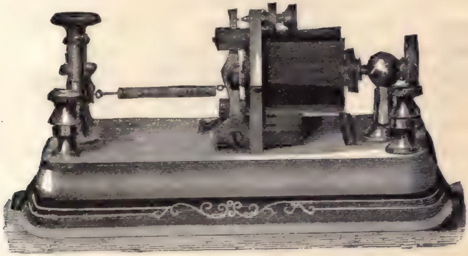


and action. At the back end of the lever there is a point *B*, and just above this point a strip of paper *C* is carried along by clockwork between two rollers at *D*. When the lever is drawn to the magnet, the point is thrown against the paper and scratches a line on it. This line will be long or short according to the time the lever is held down. The long lines are called *dashes* and the short lines *dots*. These dots and dashes correspond to the short and long intervals between the clicks of the sounder, and their combinations form the letters of the alphabet.

466. *The Relay.* — On long lines, in which there are a number of stations, the current from the main battery is

not strong enough to work the sounders with sufficient force. This necessitates the use of an instrument called the *relay*. This instrument is shown in Figure 429, and

Fig. 429.



the essential parts of it are shown in outline in Figure 430. *A* is an electro-magnet ; *l* is the lever, which turns upon an axis at *b* ; *c* is a piece of soft iron fastened across the lever in front of the electro-magnet ; *f* is a spring for pulling the lever back ; *d* and *e* are two platinum points, the former fastened to the lever and the latter stationary.

Fig. 430.

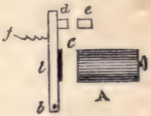
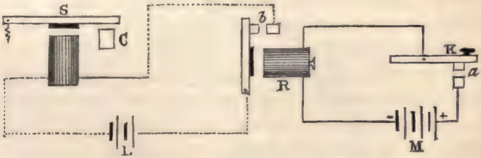


Figure 431 shows the way in which the key, relay, and sounder are connected. The full line represents the circuit

Fig. 431.



of the main battery *M*; and the dotted line, of the local battery *L*. One pole of the main battery is connected with

the anvil of the key, and the other with one end of the wire of the electro-magnet of the relay. The other end of the wire of this magnet is connected with the lever of the key at the axis. One pole of the local battery is connected to the lever of the relay, and the other pole to the electro-magnet of the sounder and then to the stationary platinum point of the relay. When the lever of the key is up, the main circuit is opened at *a*, the current is stopped, the electro-magnet of the relay is inactive, the lever of the relay is drawn back by the spring, the local circuit is opened at *b* by the separation of the platinum points, the electro-magnet of the sounder is inactive, and the bar of the sounder is thrown up by the spring. On pushing down the lever of the key, contact is made at *a*, the main circuit is closed, the electro-magnet of the relay becomes active, the lever of the relay is drawn forward, contact is made at *b*, the local circuit is closed, the electro-magnet of the sounder becomes active, and the lever of the sounder is drawn down. Thus the levers of the relay and sounder vibrate in unison, but each is worked by a different battery. The vibration of the lever of the relay is controlled by the key, and controls the vibration of the lever of the sounder by opening and closing the local circuit.

467. *The two Terminal Stations of a Line.*—Figure 432 shows the arrangement of the instruments and circuits for two terminal stations. For convenience, half of the main battery is placed at each station. There is also a key, a relay, and a sounder at each station. One pole of the main battery, say the negative, at New York is connected to the earth by a wire running to a large copper plate *E* sunk in the ground. A wire runs from the positive pole of the battery to the anvil of the key *K*, then from the lever of the key to the electro-magnet of the relay *R*, then from the relay to the line and along the line to Boston, then to the electro-magnet of the relay *R'*, then to the lever of the

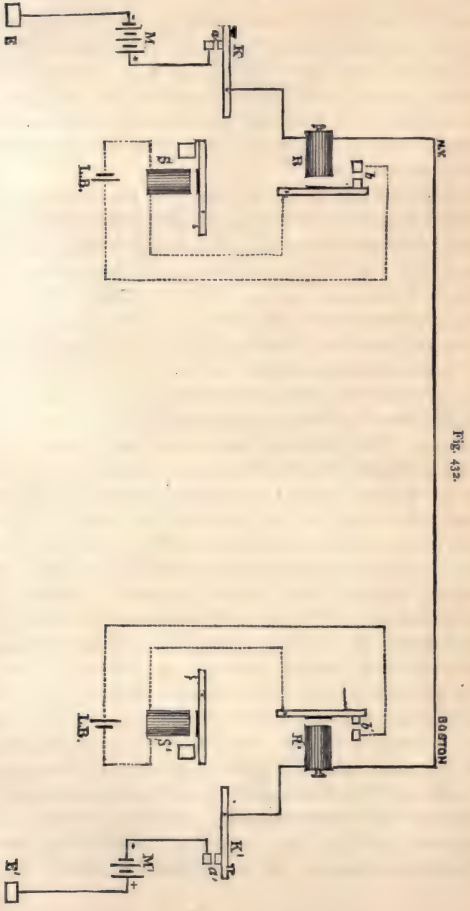


Fig. 432.

key K', then from the anvil of the key to the negative pole of this part of the main battery, and from the positive pole of the battery to the copper plate E' in the earth. The circuit is completed by the earth, the electricity passing one way over the line and back through the earth. Each local battery is connected with its relay and sounder as in the previous section.

When the line is not in operation, the main circuit is closed at each key by pulling the side lever seen in Figure 422 up against the anvil. This connects the axis of the lever with the anvil, and closes the circuit, although the levers of the keys are up. The electro-magnets of both relays are now active, the levers of both relays are drawn forward, both local circuits are closed, the electro-magnets of both sounders are active, and the levers of both sounders are drawn down. When the operator at one of the stations wishes to send a message, he pulls back the side lever of his key. This opens the main circuit, and causes all the electro-magnets to become inactive, and all of the levers to be thrown back. On working his key, the levers of both relays and of both sounders are made to vibrate. His own sounder clicks as well as that at Boston. When the operator has finished his message, he closes his key by pulling the side lever against the anvil. Should both operators start at the same instant to send messages, the fact would be revealed by the confusion of the signals given by each sounder, and one operator would close his key and wait for the other to finish. Should the operator at the receiving station desire to interrupt the one sending the message to ask him to repeat, or for any other purpose, he has merely to open his key so as to break the current.

468. *A Way Station.* — One of the simplest methods of introducing the instrument of a way station into the circuit is shown in Figure 433. *A* and *B* are two brass buttons turning on pivots at the top. Under the bottom of each

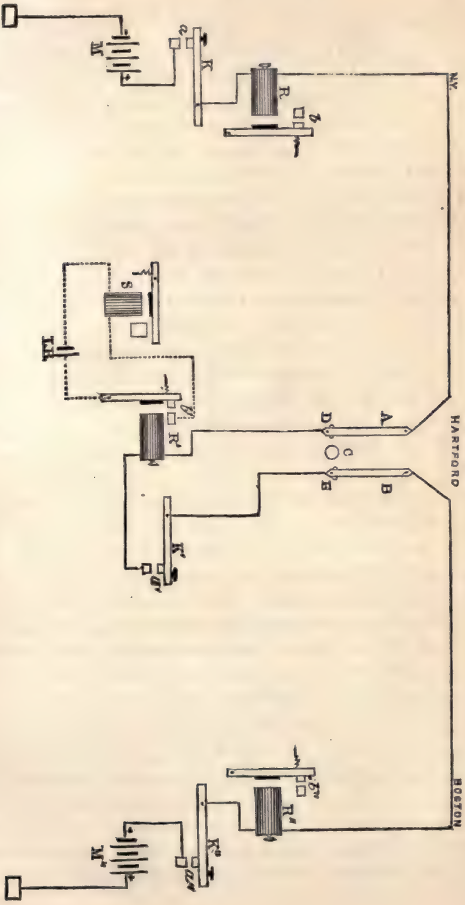


Fig. 433.

button, as it stands in the diagram, is a metallic disc D, E. A wire runs from one of the metallic discs to the electro-magnet of the key K' and thence to the anvil of the key K'. A wire runs from the other disc to the lever of the key. There is a third metallic disc at C between the buttons. When the buttons are on the discs D and E, the key and the electro-magnet of the relay are in the main circuit. The sounder and local circuit are arranged precisely as in the terminal stations. When not in operation, the key is kept closed by means of the side lever.

It will be seen at once that the levers of the relay and sounder will vibrate when the key at either terminal station is worked, and also that the levers of the relays and sounders at the terminal stations will vibrate on working the key at the way station. When the buttons A and B are both turned upon the disc C, the instrument of the way station will be *cut out* of the circuit, which will be completed through the buttons, these being now in contact with each other.

When any key at any station is worked, the sounders of every station which is not cut out will click. The name of the station for which the message is designed is first called, and only the operator at that station attends to the message.

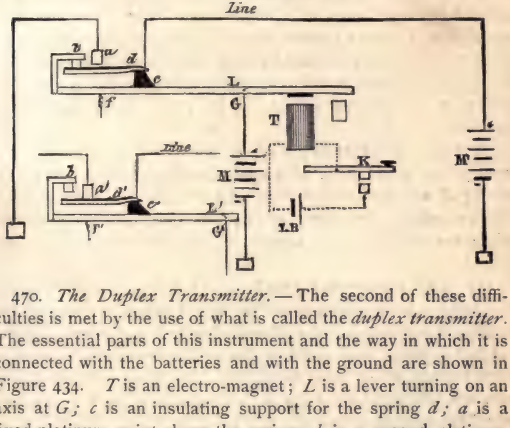
There are means at each way station to connect one of the wires with the ground and the other wire with the line on either side, so that the operator may use that side alone, in case the line is injured in any way on the other side of his station. The chief reason that the main battery is divided between the terminal stations is to enable a way station to use the line on either side in case of necessity.

II. DUPLEX TELEGRAPHY.

469. *Two Obstacles to be overcome in Duplex Telegraphy.* — By *duplex telegraphy* is meant a system of telegraphy in which

messages are sent both ways over the same wire at the same time. There must be a battery at each of the stations between which the messages are sent. In the simple Morse system, as we have seen, the relay and sounder respond to the message at the station from which it is sent as well as at that to which it is sent. The chief obstacle to be overcome in duplex telegraphy is to keep the relay and sounder from responding to the message at the station from which it is sent, so that they shall respond only at the station to which the message is sent. The second difficulty is to prevent the opening of the key at one station from opening the circuit of the battery at the other station.

Fig. 434.



470. *The Duplex Transmitter.* — The second of these difficulties is met by the use of what is called the *duplex transmitter*. The essential parts of this instrument and the way in which it is connected with the batteries and with the ground are shown in Figure 434. *T* is an electro-magnet; *L* is a lever turning on an axis at *G*; *c* is an insulating support for the spring *d*; *a* is a fixed platinum point above the spring; *b* is a second platinum point attached to the hooked end of the lever; and *f* is a spring coil for throwing the lever up. A bar of soft iron is fastened to the lever over the electro-magnet. The key and the electro-magnet of the transmitter are in the circuit of a little local battery, as shown by the dotted lines. The + pole of the distant battery *M'* is connected with the spring on the insulating support. The + pole of the battery *M* is connected with the

lever at *G*. The stationary platinum point, and the negative poles of both batteries are connected with the ground.

When the key is open, the electro-magnet of the transmitter is inactive, and the lever of the transmitter is thrown up. The platinum point *b* is in contact with the spring, and the point *a* is separated from it. The circuit of the distant battery is now closed by way of the spring *d*, the platinum point *b*, the lever and the battery *M*. The circuit of the battery *M* is closed by the contact of *b* with the spring *d*.

When the key is closed, the electro-magnet of the transmitter is active, and the lever is drawn down. As the magnet end of the lever moves down, the hooked end moves up. The spring *d* also moves up till it is stopped by the platinum point *a*. The point *b* is carried up a little higher, and is separated from the spring. *a* is now in contact with the spring, and *b* is separated from it (Figure 434). The circuit of the distant battery is now closed by way of the spring *d*, the platinum point *a*, and the ground wire connected with it, and the circuit of the battery *M* is open.

It is thus seen that as the key is closed and opened, the platinum points *a* and *b* are alternately brought in contact with the spring *d*, and that whatever may be the position of the bar of the transmitter, the circuit of the distant battery *M'* is closed, while the circuit of the battery *M* is alternately opened and closed.

471. *The Differential Duplex.* — In the *differential duplex* the relay is kept from responding to the outgoing message by making it *differential.* A *differential relay* is one whose electro-magnet is wound with double coils, so that two currents may be sent through these coils in opposite directions. When these currents are equal the relay is inactive, and when they are unequal the relay is active.

Figure 435 represents two terminal stations arranged for the duplex system. The sounders are not shown, because they are connected with the relays as in the simple Morse system, and are controlled by the vibration of the levers of the relays. Their action is the same as before. For clearness the two coils of the differential relays are represented as apart on the same iron core. They are usually wound one over the other.

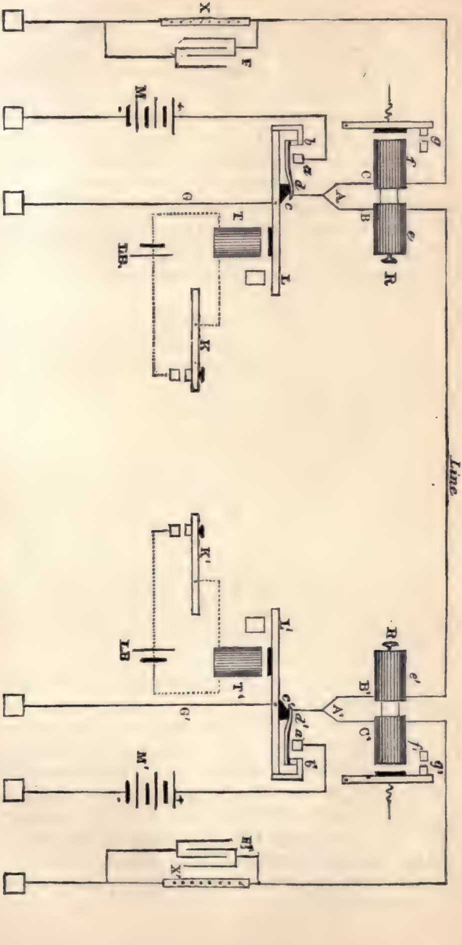


Fig. 435.

The positive pole of the battery M is connected with the stationary platinum point a of the transmitter. A wire runs from the spring d of the transmitter to the point A, where it divides into two branches B and C. The branch C traverses the coil f of the relay magnet, and then passes directly to earth through the resistance box X. The branch B traverses the coil e of the relay magnet and then passes to the line. The battery M' at the other station is connected to the transmitter and relay in exactly the same way. The negative poles of both batteries and the levers of the transmitters are connected with the ground. The resistance boxes X and X' are adjusted so that the resistance of the branch C or C' shall be equal to that of the branch B or B', including the whole line.

When the key K is closed the electro-magnet of the transmitter is made active, the lever of the transmitter is drawn down, the spring d is separated from b and brought in contact with a, and the circuit of the battery M is closed.

The current from this battery, on reaching the point A, divides into two equal parts; one of which passes through the wire C, the coil f and the resistance box X to the earth and back to the negative pole of the battery; the other passes through the wire B, the coil e, and the line to the distant station. It then passes through the coil e', the wire B', the spring d', and thence to the earth, either by the point a' and the battery M', or by the point b', the lever and the ground wire G', according as a' or b' is in contact with the spring d'. As the outgoing current divides equally at A, the magnet R will remain inactive while the portion which passes over the line will make R' active. Hence R' only will respond to the current sent from the battery M. In the same way it may be seen that R alone will respond to the current sent from the battery M'.

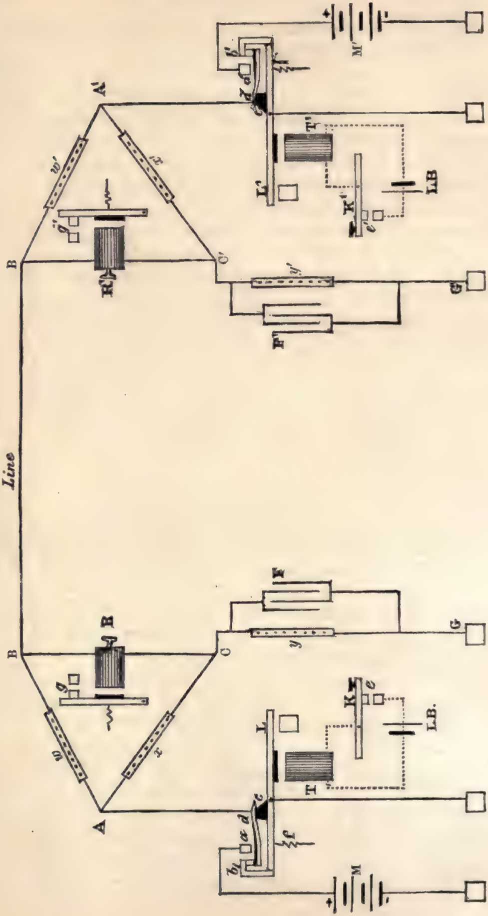
When currents are sent from both batteries at the same time, if the batteries are in opposition, as in the diagram, the currents from the two batteries will more or less completely neutralize each other in the *line branch*, BB', without neutralizing each other at all in the earth branches, C and C'. The currents will therefore be unequal in the two sets of coils at each relay, and both the electro-magnets will be active. The electro-magnet at the *left* will be active just as long as the key at the *right* is closed, and *vice versa*.

472. *The Use of Condensers with the Duplex.* — As has already been stated, a part of the electricity that flows into a wire is used in charging it. Now, when contact is broken at *a*, it is found that a portion of the charge which the line has received from the battery *M* rushes to earth through the coil *e*, the spring *d*, the point *b*, and the ground wire *G*. This current would make the magnet *R* active, and give a false signal on the sounder connected with this relay, were it not balanced by an equal current sent back through the coil *f*. This return current is obtained by means of the condenser *F*. This condenser is charged by the electricity flowing through the branch *C* to the earth. When contact is broken at *a*, the coatings of the condenser connected with the wire near the resistance box at once discharge themselves through the wire to the earth. As the resistance is much less by way of the coil *f*, and the spring *d*, and the ground wire *G*, than through the resistance box *X*, the greater part of the discharge takes this route. The condenser is adjusted so that the discharge from it through *f* is just equal to the discharge from the line through *e*. The condenser *F'* at the other station acts in a similar way.

473. *The Bridge Duplex.* — Another way to keep the relay from responding to the outgoing current is to place it on a bridge. This arrangement is shown in Figure 436. The keys, transmitters, and batteries are arranged exactly as in the differential duplex. At *A* the circuit divides so as to form a bridge, the four branches of which are *A B*, the line, *A C*, and *C G*; and the bridge proper *B C*. The resistance boxes *w*, *x*, and *y* are introduced into three of these branches, and adjusted so that the resistance of *A B* is to that of the line as the resistance of *A C* is to that of *C G*. The relay *R* is introduced into the bridge *B C*. This is an ordinary relay. The arrangement at *A'* is in all respects similar to that at *A*.

The outgoing current from the battery *M* divides at *A* into two portions, one of which passes through *A C* and *C G* to the earth, and the other through *A B* and the line to the distant station. None of the outgoing current crosses the bridge *B C*, and hence the relay *R* does not respond to this current. As the portion of the current which has traversed the line crosses to *B'* it again divides, a part of it going through *B'C'* to the earth,

Fig. 436.



and another part of it through $B' A'$ and the transmitter to the earth. The first portion works the relay R'. In a similar way, none of the current sent back from the battery M' will pass through the wire $B' C'$ so as to work the relay R', while a portion of it will cross $B\ C$ and work the relay R. Thus, R and the sounder connected with it will deliver only the message sent by key K', and R' and the sounder connected with it, only the message sent by key K.

The condensers F and F' are used to send back through $C\ B$ and $C' B'$ discharges to neutralize those sent from the line through the wire on breaking contact at a and a'.

III. QUADRUPLEX TELEGRAPHY.

474. *The Principle of the Quadruplex.* — By *quadruplex telegraphy* is meant a system of telegraphy in which four messages may be sent over the same wire at the same time, — two in each direction. To send two messages the same way at the same time, it is necessary to have one relay worked by changing the direction of the current, and one by changing the strength of the current; also to have a transmitter controlled by one key arranged so as to change the direction of the current, and a transmitter controlled by the other key arranged so as to change the strength of the current.

475. *The Polarized Relay.* — The *polarized relay* differs from an ordinary neutral relay simply in having a small steel magnet on the lever in place of the bar of soft iron. There is usually no spring acting on the lever. When the current passes through the coils of the electro-magnet in one direction, the poles of the electro-magnet are unlike those of the permanent. There is then attraction, and the lever is drawn forward. On reversing the direction of the current the poles of the electro-magnet are reversed, and become like those of the steel magnet in front of them. There is now repulsion, and the lever of the relay is thrown back.

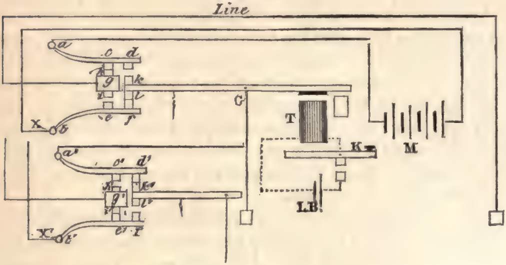
476. *The Pole-Changer.* — The transmitter used for changing the direction of the current is called the *pole-changer*. The essential parts of this instrument and its connection with the key and a battery are shown in Figure 437. The pole-changer is connected with the key in precisely the same way as the duplex transmitter. At the end of the lever away from the electro-

magnet are two springs, *a* and *b*. On each of these springs are two platinum points (*c*, *d*, and *e*, *f*). Between the springs is a back-stop *g*, having two platinum points, *h* and *i*, upon it, facing the points *c* and *e*. The end of the lever has also two platinum points, *k* and *l*, upon it, facing the points *d* and *f*.

The back-stop *g* is connected with the line, the spring *a* with the negative pole of the battery, the spring *b* with the positive pole of the battery, and the lever with the ground.

When the key is closed, the electro-magnet of the pole-changer is active, the lever is drawn to the magnet, and the other end of the lever is raised, and contact is made between *d* and *k* and between *e* and *i*, and broken between *c* and *h* and

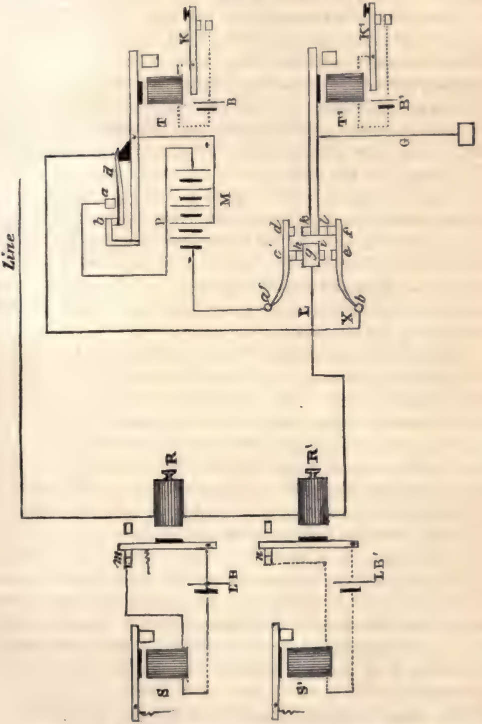
Fig. 437.



between *l* and *f*. The positive pole of the battery is now connected with the line through the points *e* and *i*, and the negative pole with the earth through the points *d* and *k*. When the key is open, the electro-magnet of the pole-changer is inactive, and the magnet end of the lever is thrown up, and the other end of the lever thrust down. Contact is thus broken between *d* and *k* and between *e* and *i*, and made between *l* and *f* and between *c* and *h*. The negative pole of the battery is now connected with the line through the points *c* and *h*, and the positive pole with the earth through the points *f* and *l* (Figure 437). As the pole-changer end of the lever rises, the spring *b* follows it until it is stopped by the platinum point *i* on the back-stop *g*. At this instant the point *k* strikes the point *d*. The lever then raises

the spring *a*, and so breaks contact between *c* and *h*. At the same time it leaves the spring *b* behind, and so breaks contact between *f* and *l*. The reverse takes place when this end of the lever is lowered.

Fig. 438.



477. *Simultaneous Transmission of two Messages in the Same Direction on a Wire.* — The arrangement of the instru-

ment at a terminal station for the simultaneous transmission of two messages in the same direction is shown in Figure 438. T is a duplex transmitter, employed for changing the strength of the current. It is worked by the local battery B and the key K. T' is a pole-changer, used for changing the direction of the current. It is worked by the local battery B' and the key K'. R is an ordinary neutral relay, and S is its sounder. R' is an ordinary polarized relay, and S' is its sounder. These sounders are worked by the local batteries $L\,B$ and $L\,B'$.

M is the main battery. The positive pole of this battery is connected with the platinum point a of the duplex transmitter, and the negative pole with the spring a of the pole-changer. The spring d of the transmitter is connected with the spring b of the pole-changer. The back-stop g of the pole-changer is connected with the line through the electro-magnet of the relays R' and R. The lever of the transmitter is connected with the positive plate P of the main battery, and the lever of the pole-changer is connected with the ground. At the other terminal station there will be precisely the same instruments, arranged in precisely the same way.

When the key K is open, the electro-magnet of the transmitter is inactive, the magnet of the lever is thrown up, and the hooked end is thrust down. The platinum point b is in contact with the spring d, and the point a is separated from it. The positive plate P of the main battery, or the positive pole of $\frac{1}{4}$ of the battery, is now connected with the spring b of the pole-changer through the point b of the transmitter. The remaining $\frac{3}{4}$ of the battery are cut out of the circuit, since the point a is separated from the spring d of the transmitter.

When key K is closed, the electro-magnet of the transmitter is active, and the magnet end of the lever is drawn down, and the other end is thrust up. The platinum point a is now brought into contact with the spring d, and b is separated from it. The positive pole of the whole battery is now connected with the spring b of the pole-changer through the point a of the transmitter.

The effect of closing key K is to put the whole battery in circuit; and of opening it, to cut out a part of the battery from the circuit.

When key K' is open, the magnet of the pole-changer is inactive, the magnet end of the lever is up, and the other end down. The positive pole is now connected with the ground through the spring b, the points f and l, the lever, and the wire G; and the negative pole is connected with the line through the spring a, the points c and h, and the back-stop g.

When K' is closed, the electro-magnet of the pole-changer is active, the magnet end of the lever is pulled down, and the other end is thrust up. The positive pole will now be connected with the line through the spring b, points e and i, and the back-stop g; and the negative pole is connected with the ground through the spring a, the points d and k, the lever, and the wire G.

The effect of closing K' is to put the positive pole of the battery to the line, and the negative pole to the earth; and of opening it, to put the negative pole to the line, and the positive pole to the earth. In other words, closing K' reverses the direction of the current.

The neutral relay R is so adjusted that it requires the current from the whole battery to overcome the tension of the spring f, so as to pull the lever forward and break contact between the platinum points at m. The action of this relay is independent of the direction of the current. The local circuit of the sounder S will therefore be closed when key K is open, and opened when key K is closed; that is to say, the sounder S delivers the message sent by key K, and that message only.

The polarized relay R' is so arranged that it can be worked by the smaller portion of the battery as well as by the whole battery, and so that like poles on the electro-magnet and on the steel magnet are together when the key K' is open. In this case the lever is repelled, and contact made at n, and the level circuit of sounder S' is closed. On closing key K', the line current and the poles of the electro-magnet R' are reversed. The steel magnet is now attracted, the lever drawn forward, and contact broken at n. This opens the local circuit of the sounder S'. As the relay R' is worked only by changing the direction of the current, it responds only to the action of key K'. As this relay can be worked by a part of the battery as well as by the whole, R' will respond to the working of K' whether K is open or closed.

Of course, the instruments at the distant station would respond in the same way as these in this station, as they are in the same circuits. Thus, two messages may be sent out at the same time, — one by each of the keys, — and each will be delivered by the corresponding sounder without any confusion. Of course, the two sounders are placed so far apart that the operator who is attending to one is not confused by the clicking of the other.

478. *The Quadruplex System.* — By using differential relays, or by placing the relays on a bridge, the sounders would be kept from responding to the outgoing message, and would at the same time be in readiness to deliver incoming messages, as in the duplex system; that is, by *duplexing* the arrangement just described, four messages may be sent simultaneously over the same wire, — two in each direction. The differential method of duplexing is the one ordinarily used in the quadruplex system.

The use of the duplex and quadruplex system is rapidly extending. The Western Union Company already use the quadruplex system on 200 lines. The tendency of these two systems is to drive the simple Morse system entirely from the field, except on lines where there is very little business.

IV. SUBMARINE TELEGRAPHY.

479. *The Cable.* — In submarine telegraphy, the conducting wire, instead of being insulated on poles by means of glass insulators, is insulated by being enclosed in an insulating sheath. The insulator used should be sufficiently tough not to break in the operation of laying the cable, and it should at the same time have as low a specific inductive capacity as possible. The conductor is a strand of rather fine copper wire. The insulating sheath is of gutta-percha. This is protected by a layer of tarred hemp, and the whole is surrounded by iron wire for greater strength. The iron wire is usually protected by an outer coating of some kind. It is necessary that the conducting wire should be very carefully insulated; and it is desirable to have the specific inductive capacity of the insulator as low as possible.

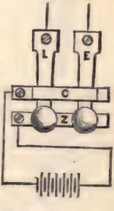
480. *Duration of the Variable State in a Cable.* — While a wire is becoming statically charged or discharged, the current at the distant end of the wire is in a variable state. When the

wire is becoming charged, the current at the distant end is feeble at first, and rises gradually to its maximum strength. It then remains of constant strength till the current at the other end is stopped and the wire begins to discharge itself. It then gradually dies away. The duration of this variable state increases with the capacity of the conducting wire. On land lines it is exceedingly short, but in a long submarine cable, owing to its very much greater capacity, the variable state lasts several seconds. When a signal is sent from Valentia, it is about two tenths of a second before it begins to be felt at Newfoundland, and it is three seconds before the current reaches its maximum strength; and if the cable were left to discharge itself in its own way, the current would be equally long in stopping.

481. *The Transmitting Key.* — Owing to the feebleness of the current which first reaches the distant end of the cable, in order that the signals may be received promptly, it is necessary to use a very sensitive receiving instrument; and owing to the duration of the variable state on starting or stopping the current, in order that the signals may follow each other rapidly, it is necessary to provide some means for promptly discharging the cable.

The transmitting key is shown in Figure 439. *E* and *L* are two levers connected respectively with the earth and the line. When not depressed, both of these levers rest against the upper bar *C*, which is connected with the positive pole of the battery. When either is depressed, it is separated from the upper bar and is brought into contact with the lower bar *Z*, which is connected with the negative pole of the battery. On depressing *E*, the positive pole of the battery is connected with the cable and the negative pole with the earth. On releasing *E* and depressing *L*, the negative pole of the battery is connected with the cable and the positive pole with the earth. By depressing the levers alternately, the direction of the current in the cable is reversed.

Fig. 439.

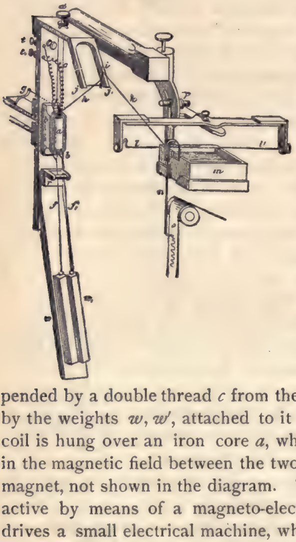


482. *The Receiving Instrument.* — Thomson's reflecting galvanometer is one of the receiving instruments employed on long submarine cables. As the direction of the current in the cable is reversed, the spot of light, reflected from the mirror, moves

towards the right or towards the left as the case may be. The letters are indicated by combinations of these movements, as by the combinations of the long and short intervals in the case of the Morse sounder. This galvanometer is a very sensitive receiver, but it is very fatiguing to the operator to watch the motion of the spot of light.

The *siphon recorder* is another very sensitive receiving instrument invented by Sir William Thomson. This instrument is shown in Figure 440. The pen is a fine glass tube *n* bent in the form of a siphon. The short arm of this siphon dips into a reservoir of ink *m*, and the long arm is bent at right angles so as nearly to touch a ribbon of paper *o*, which is moved along at a uniform rate by machinery.

Fig. 440.



The pen is hung on a thread *l l'*, and is guided by a thread *k i h*, which is attached to a small coil *b*. This coil is connected with the cable by means of the wires *t*, *t'*. It is suspended by a double thread *c* from the point *d*, and is held steady by the weights *w*, *w'*, attached to it by the threads *f*, *f'*. The coil is hung over an iron core *a*, which it does not touch, and in the magnetic field between the two poles of a powerful electro-magnet, not shown in the diagram. This electro-magnet is kept active by means of a magneto-electrical machine, which also drives a small electrical machine, which charges the ink in the reservoir and the paper with unlike electricities. The attraction of these electricities maintains a steady flow of ink through the pen, and causes it to escape from the point in minute drops which make a straight line on the paper when the pen is still. As the direction of the current in the cable is reversed, the little coil *b* turns in the magnetic field a little to the right or left,

according to the direction of the current, on a vertical axis. As the coil turns, it alternately pulls and releases the thread $h\,i\,k$, and causes the end of the siphon pen next to the paper to swing a little to the right and left, according to the direction in which the coil turns. As the end of the pen moves to the right and left, the ink flowing from it makes a waving line on the paper, which indicates every change in the current of the cable. The movements of the end of the pen thus recorded on the paper correspond to the movements of the galvanometer needle indicated by the spot of light reflected from the little mirror.

483. *Varley's Method of working the Cable with Condensers.* — In Varley's method, the rapid discharge of the cable is effected by means of condensers.

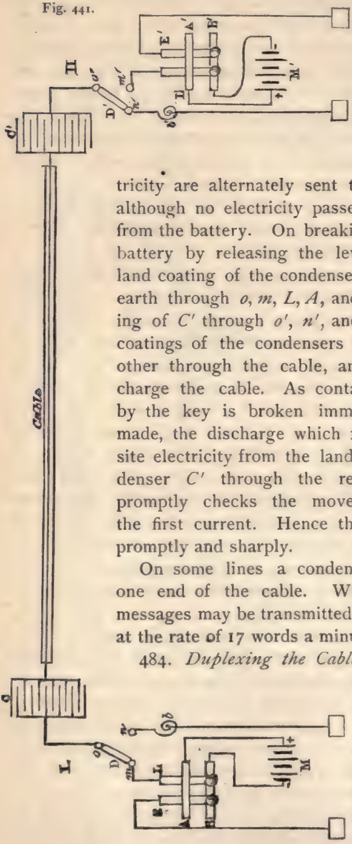
The general arrangement of the condensers and the other parts of the cable apparatus is shown in Figure 441. C and C' are two condensers, one at each end of the cable. One of the coatings of each of these condensers is connected with the cable, and the other coating with the apparatus on land. D and D' are metallic buttons turning on pivots at o and o' between two metallic discs m, n and m', n'. m and m' are connected with the levers L and L' of the keys; n and n' are connected with the coils b and b' of the receiving instruments, which may be either galvanometers or siphon recorders. The other end of each of these coils is connected with the earth. The levers E, E' of the keys are also connected with the earth. M and M' are the batteries, the positive poles of which are connected with the bars A, A' of the keys, and the negative poles with the bars B, B'. The button D is arranged for transmitting a message, and the button D' for receiving it.

On depressing the lever E of the key at the sending station, positive electricity is sent to the land coating of the condenser C. This positive electricity holds negative electricity upon the cable coating of this condenser, and drives positive electricity to the cable coating of the condenser C', which in turn holds negative electricity on the other coating of the condenser, and drives positive electricity into the ground, through the coil b' of the receiving instrument at the receiving station.

On depressing the lever L, negative electricity is sent to the land coating of the first condenser, and, by a series of inductive

actions similar to those just described, negative electricity is sent

Fig. 441.



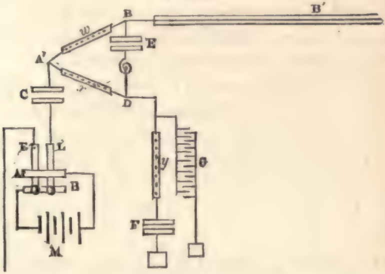
from the land coating of the condenser C' through the coil b to the ground. Thus, by alternately depressing the keys E and L, positive and negative electricity are alternately sent through the coil b', although no electricity passes through the cable from the battery. On breaking contact with the battery by releasing the lever of the key, the land coating of the condenser C is discharged to earth through o, m, L, A, and E; the land coating of C' through o', n', and b'; and the cable coatings of the condensers discharge into each other through the cable, and so promptly discharge the cable. As contact with the battery by the key is broken immediately after it is made, the discharge which follows of the opposite electricity from the land coating of the condenser C' through the receiving instrument promptly checks the movement produced by the first current. Hence the signals are given promptly and sharply.

On some lines a condenser is used at only one end of the cable. With the condensers, messages may be transmitted on an Atlantic cable at the rate of 17 words a minute.

484. *Duplexing the Cable.* — The cable may be duplexed by placing the receiving instrument on a bridge, as shown in Figure 442. The battery and key are arranged as before. C is the sending

condenser and E the receiving condenser. The circuit divides at A' into two portions, which pass around the bridge $B D$. The four branches of the bridge are $A B$, $B B'$, $A D$ and $D F$. The receiving coil b, as well as the receiving condenser E, is on the bridge. The resistance boxes, w, x, y, are adjusted so that none of the outgoing current shall cross the bridge $B D$. The resistance of y is made as large as that of the cable, and the condenser G connected with it is made to have as great a capacity as the cable. The condenser is arranged in such a way that it shall discharge itself at the same rate as the cable on breaking contact at the key, in order that the discharge from the condenser

Fig. 442.



may exactly balance that from the cable on breaking contact, so that there may be no movement of the receiving instrument.

The arrangement of the bridge at the other end of the cable is precisely the same as at this. The Direct United States Cable has been successfully duplexed. The only thing needed to duplex successfully any cable is to make the artificial line $D G F$ exactly equal to the cable in resistance, capacity, and rate of discharge. The condenser F represents the one at the other end of the cable.

F. Transmission of Power by means of Electricity.

485. *Electro-Motors.* — The current produced by moving a magnet near a wire, or a wire near a magnet, always opposes the motion which produces it ; that is to say, it

tends to produce motion in the opposite direction. Hence if a current of electricity from any external source were sent through the coils of a magneto-electrical machine in the direction of the one produced in these coils by the action of the machine, it would cause the cylinder to revolve in the opposite direction to that in which it must be turned to produce a current. Hence electricity when sent through the coils of such a machine becomes a source of power.

A machine driven by electricity is called an *electro-motor*. There are various forms of electro-motors, but the most efficient are those constructed on the principle of the reversibility of dynamo-electrical machines. It is proposed to employ electricity as a motive power for a great variety of purposes.

Companies have been formed to develop electric currents at one or more centres in cities, and send them through wires laid in the streets to the houses, to be used for a variety of domestic purposes, such as driving clocks, working sewing-machines, pumping water, etc.

It is thought that electricity will be found to be the medium by which power can be most efficiently and economically transmitted to a distance. For instance, when water-power is abundant in places remote from the localities where the power is needed, the energy of the water may be converted into that of electricity by means of dynamo-electrical machines, then the electricity conducted to the distant points through wires, and used as a source of power with similar dynamo-electrical machines.

G. Electro-Thermal Action.

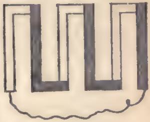
486. *Thermo-Electric Piles.* — When two metals are soldered together, so as to form a closed circuit, as shown in Figure 443, and one of the junctions is heated more than the other, a current flows around the circuit. The direction and strength of the current vary with

Fig. 443.

the metals used. Such a combination of two metals is called a thermo-electric pair. Antimony and bismuth form the best combination among the metals. In this combination the current flows across the heated junction from the bismuth to the antimony,

With a single pair of metals only a feeble current is obtained. These pairs may be combined so as to form batteries, or *piles*. The pairs are soldered together at alternate ends, as shown in Figure 444. Several hundred pairs are often combined in a pile.

Fig. 444.



The least difference of temperature between the ends of such a pile gives rise to a current. When used with a delicate galvanometer the thermo-electric pile is an exceedingly sensitive differential thermometer. No current is obtained from the thermo-electric pile when the two faces are heated equally.

487. *The Thermal Balance.* — It is found that the resistance of a conductor, as a rule, increases as its temperature rises. Professor Langley has taken advantage of this fact to construct a thermal instrument of remarkable sensibility, called the *thermal balance.* He introduces a number of strips of steel, $\frac{1}{32}$ of an inch wide and $\frac{1}{8000}$ of an inch thick, side by side, into one of the two branches of a circuit. The two branches are adjusted so as to divide the current equally when the steel strips are at the same temperature as the rest of the circuit, and are connected to the coils of a differential galvanometer. On *heating* or *cooling* these strips of steel, their resistance is either increased or diminished, the equality of the currents in the two branches of the circuit is destroyed, and the needle of the galvanometer is deflected. This instrument is much more delicate than the thermopile described above, and what is even more important, is far more rapid in its action. It will indicate a change of temperature of $\frac{1}{50000}$ part of a Fahrenheit degree. Mounted in a reflecting telescope, it will indicate the heat from a man or other animal in a field many yards distant.

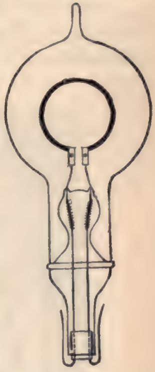
488. *The Development of Heat by means of the Current.* — Whenever a powerful current of electricity flows through a wire it heats it. The finer the wire, and the lower the conducting power of the material of which it is composed, the more intense the heat developed. The more powerful the current employed, the more intense the heat obtained with the same conductor. Fine wires of the most refractory metals are heated white-hot, and even fused, on the passage of powerful currents.

489. *Electric Illumination by Incandescence.* — There has been for a long time an effort to make electricity available as a source of light, and at last the many practical difficulties that have been met with seem to have been nearly, if not quite, surmounted. Illumination by means of a poor conductor heated to a white heat on the passage of the current, is called illumination *by incandescence.* The great difficulty encountered in illumination by incandescence is that the conductor which is heated to incandescence by the current is also apt to be destroyed by the current. Even so refractory a substance as platinum is very likely to fuse when heated to incandescence. Hence there is no dependence to be placed upon a lamp in which a metallic wire is heated to incandescence by the current. If the current is sent through a very thin rod of carbon, the carbon becomes heated to incandescence; but at the high temperature the carbon is liable to be destroyed by combining with the oxygen of the air. Even when the carbon is placed in an exhausted receiver, or in one which has been first exhausted of air and then filled with nitrogen or some other gas which is a non-supporter of combustion, the carbon filament is liable to disintegration.

490. *The Edison Lamp.* — The Edison lamp for incandescence is shown, in section, in Figure 445. The upper portion of the lamp is a glass globe, from which the air has been exhausted, and which is hermetically sealed. In

the centre of this globe is the carbon filament, bent in the form of a ring. The ends of this filament are held in little clamps, which are connected with the platinum wires which pass through the glass of the smaller globe under the ring, and thence out through the bottom of the lamp, where they are connected with the wires of the circuit.

Fig. 445.



The permanent success of this and similar lamps for illumination depends solely upon whether the carbon filament is found, in practice, to be sufficiently durable. The Edison filament is constructed of bamboo-wood. The bamboo filament, before it is bent and carbonized, is shown in Figure 446. It is from five to seven inches in length, and from $\frac{1}{64}$ to $\frac{1}{32}$ of an inch in diameter. It is first worked to a uniform size throughout, and then bent into a ring and carbonized under pressure. The resistance of the loop is from 100 to 300 ohms, and the amount of light that can be safely obtained from it varies from 2 to 10 candles.

Fig. 446.

These lamps will be arranged in the houses just as gas-jets are now, and electricity will be conducted to them by wires in the streets, just as gas is conducted to the gas-jets by pipes in the streets.

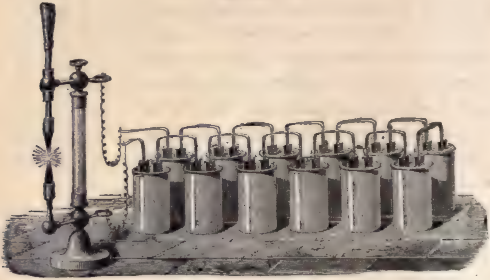
Edison's plan is to measure the electricity used in each house by a kind of voltameter, in which sulphate of copper is decomposed instead of sulphuric acid. The copper is deposited on one of the electrodes and so increases its weight. The increase in weight of the plate will show the

amount of electricity which has passed through the instrument.

Illumination by incandescence is especially adapted for lighting rooms of the ordinary size.

491. *The Voltaic Arc.* — If two pencils of coke carbon are introduced into a circuit through which a powerful current of electricity is passing so as to be in contact at their ends, on separating these pencils a little, intense light and heat will be developed at the point of separation (Figure 447). The ends of the pencils will be heated white-hot,

Fig. 447.



and they will be connected by a luminous bridge. This bridge is called the *voltaic arc*. The light and heat of the voltaic arc are the most intense that can be obtained by artificial means.

If the carbons are separated far enough to stop the current, it will not start again till they have been again brought in contact. After the current has been started, it will continue to flow after the carbons are separated, provided they are not separated too far. The reason the current will continue to flow after the carbons have been separated, though it will not begin to flow till they have been brought into contact, is this. As the carbons begin

to separate, the current which is passing detaches little particles from each of them and transfers these to the other carbon, and so bridges over the space between the points with carbon dust. The air thus filled with particles of carbon offers less resistance to the current than the air free from carbon dust which separates the points

Fig. 448.

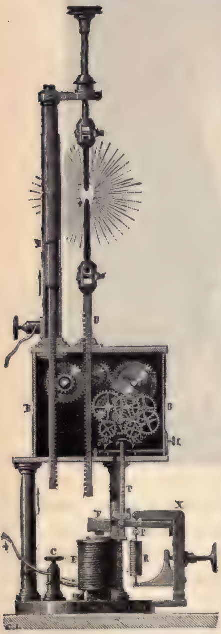
before they are brought into contact. Another reason is that heated air offers less resistance than cold air. The intense heat of the voltaic arc is due to the resistance which the current encounters in the space between the carbon points.

The end of the positive carbon becomes concave, and that of the negative carbon pointed, as shown in Figure

448. Both carbons are consumed, but the positive more rapidly than the negative.

492. *Illumination by the Voltaic Arc.* — In order to obtain illumination by the voltaic arc, a lamp is needed to keep the carbons all the time at the right distance apart, and to bring the points together, in case the current should stop, and then to separate them again when the current has started.

Fig. 449.

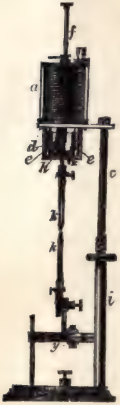


Illumination by the voltaic arc is too intense for rooms of the ordinary size, but is especially adapted for out-door illumination, and for large halls and workshops.

493. *Foucault's Regulator.* — When it is necessary to keep the light all the time at the same point, as in the lantern for projection, there is needed a lamp which shall move each carbon at the rate at which it is consumed. The best lamp for this purpose is *Foucault's regulator*. This lamp is shown in Figure 449. The points are moved by means of clock-work, which is so constructed that it can be made to move the points either together or apart. The clock-work is controlled by an electro-magnet *E* by means of the lever *F*. The current passes through the coil of this electro-magnet on its way to the carbons. When the carbons become too far apart, the current is weakened, the lever *F* is released, and the clock-work is made to turn so as to move the carbons together. When the carbons

come too near together, the current becomes strong enough to draw the lever down, and this causes the clock-work to turn so as to separate the points. When the points are at just the right distance apart, the lever F is held in such a position as to stop the clock-work entirely.

Fig. 450.



494. *The Brush Lamp.* — For ordinary illumination, it is not necessary that the light should be maintained at the same point. One of the best lamps for purposes of general illumination by the voltaic arc is the *Brush lamp*, which is shown in Figure 450. The upper carbon is fastened to a rod *f* which passes loosely through the centre of the hollow iron core *d* of the coil *a*. This core is partially supported by the adjustable springs *e e*. A metallic washer *h* surrounds the rod just below the core *d*. This disc rests on one side of the lifting finger *g* (Figure 451) attached to the core *d*. Just above the washer, on the other side, is the head of the screw *x*. The current which passes between the carbon points also passes through the coil at the top. When the current becomes too strong by reason of the carbons coming too near together, the core is pulled up into the coil, and the

Fig. 452.

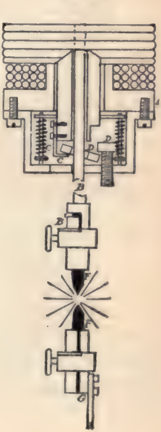
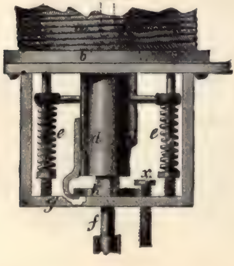


Fig. 451.



lifting finger tilts the washer (Figure 452) so as to clamp the rod that holds the upper cárbon, and it at the same time raises the rod till stopped by the screw-head on the opposite side. When the current becomes too feeble by the carbons getting too far apart, the core is released, the washer is dropped, and the rod slides freely through it.

H. Radiant Matter.

495. *Changes produced in a Vacuum Discharge by Variation of Pressure.* — If the terminals of a vacuum tube are connected with a large induction coil, and the tube is arranged so that it may be gradually exhausted by means of a mercurial pump, when the pressure has been reduced to a small fraction of a millimetre the whole tube will be filled with a bright light. As the exhaustion proceeds, the luminous stream breaks up into a number of discs of light called *striæ.*

The stratification of the discharge varies greatly under different circumstances. Some of the forms of stratification are shown in Figures 453 and 454.

496. *Crookes's Discovery.* — Mr. William Crookes has discovered that when the exhaustion of a vacuum tube is carried considerably beyond that point which gives the best striæ and luminous effects, a new set of phenomena not hitherto observed are produced ; and the residual gas develops so many new properties that he considers himself justified in saying that gas, when at these low pressures, may be regarded as matter in a fourth or ultra-gaseous state. To this he has given the name of *Radiant Matter.*

According to Mr. Crookes, the states of matter are four, as follows : —

1. Solid.
2. Liquid.
3. Gaseous.
4. Radiant.

The pressure at which these new phenomena are best seen is about one millionth of an atmosphere. This is about $\frac{1}{3000}$ of the pressure of an ordinary vacuum tube. The effect of the

Fig. 453.

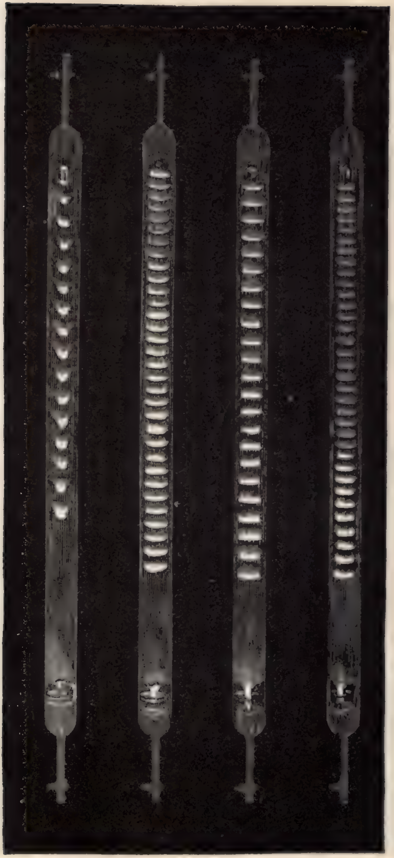
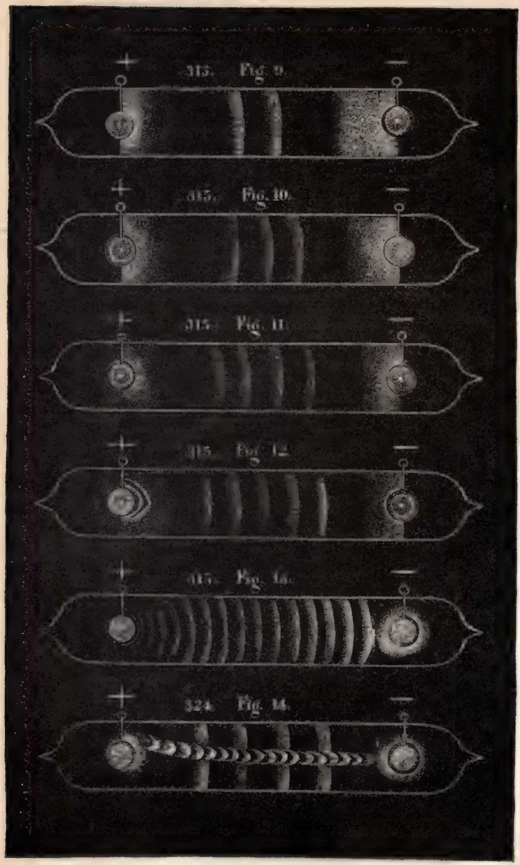


Fig. 454.



diminution of the pressure upon a gas is to increase the distance between the molecules and the length of their free paths.

Suppose a box containing a cubic foot of hydrogen at the ordinary density were opened in a cubical room measuring 100 feet each way and being a perfect vacuum. The hydrogen would fill the room, and its rarefaction would represent that of a pressure of one millionth of the atmosphere. The molecules of the hydrogen were originally about one seven-millionth of an inch apart, and the mean length of their free paths about $\frac{1}{280000}$ of an inch. After being rarefied to a millionth of the atmospheric pressure, the molecules will be one seventy-thousandth of an inch apart, and the mean length of their free paths will be about four inches.

Were a cubic foot of this rarefied hydrogen opened into a second exhausted room of the same dimensions as the first, the rarefaction would be increased a millionfold. The molecules would now be about one seven hundredth of an inch apart, and the mean length of their free paths about sixty miles. In this state of exhaustion, which is about a million times beyond that attainable by a good mercurial pump, there are still no less than 340 million molecules in every cubic inch.

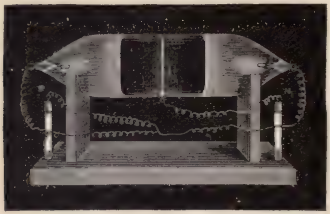
Were the rarefaction increased a millionfold by transferring a cubic foot of the gas from the second room to a third exhausted room of the same dimensions as the first, the molecules would be about one seventh of an inch apart, and their free paths about 60 million miles long. It would take a molecule of hydrogen, which ordinarily moves about three times as fast as a cannon ball, nearly two years to traverse its free path under these circumstances.

497. *The Dark Space at the Negative Pole.* — In all well-exhausted vacuum tubes a small dark space surrounds the negative pole during the discharge. Crookes found that the dark space increases in length as the exhaustion proceeds. He illustrated the effect of change of pressure on the dark space by the use of the tube shown in Figure 455. The negative pole at the centre was in the form of a metallic disc. The two end poles were connected together and made the positive terminal. With a rather low exhaustion the dark space extended only a little way each side of the pole, but as the exhaustion was

improved the dark space extended till it became an inch in length.

He accounts for the increase as follows: Molecules of gas are driven off from the negative pole, and as long as they do

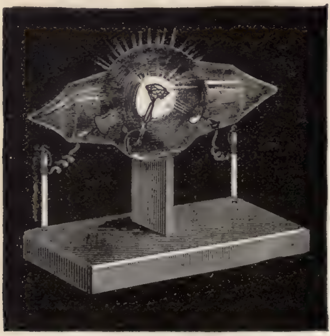
Fig. 455.



not come into collision with any other molecules, they do not produce any light. The space over which they travel without collision will be dark.

When, by diminishing the pressure, the mean free path is lengthened, the dark space increases.

Fig. 456.

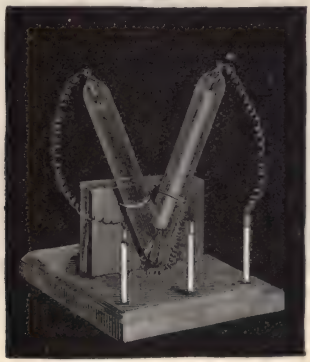


498. *Phosphorescence developed by Radiant Matter.* — We have seen that the radiant matter within the dark space develops

luminosity only when the molecules dart against other molecules of the residual gas. If the exhaustion is carried to a sufficient point, there will be no collision of the molecules of the gas, the molecules being arrested only on striking against the sides of the tube. When the molecules in this condition strike against any suitable solid they develop a greater or less degree of phosphorescence, according to the nature of the body. Crookes finds that very many solids become phosphorescent under the molecular blows of radiant matter, and that diamond is the most sensitive of all substances.

He supported a diamond on a little stand in the centre of a globe, as shown in Figure 456, and directed the molecular discharge upon it from below by means of the terminals seen at the right and the left in the figure. In a darkened room the diamond was as bright as a candle.

Fig. 457.

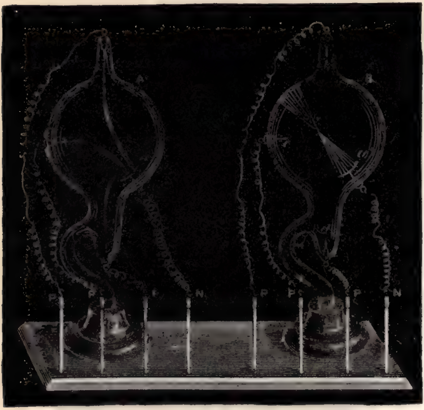


499. *Radiant Matter travels in Straight Lines.* — Figure 457 represents a V-shaped vacuum tube, with a pole at each extremity. On making the pole at the right negative and the one at the left positive, the whole of the right arm was flooded with green light, but at the bottom it stopped sharply and would not turn the corner to get into the left side. When the current

was reversed and the left pole made negative, the green changed to the left side, always following the negative pole, and leaving the positive side with scarcely any luminosity.

To produce the ordinary phenomena exhibited by vacuum tubes, it is customary, in order to bring out the striking contrasts of color, to bend the tubes into very elaborate designs. The luminosity caused by the phosphorescence of the residual gas follows all the convolutions into which skilful glass-blowers can manage to twist the glass. The negative pole being at one end

Fig. 458.

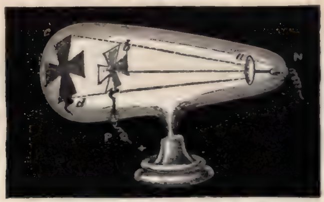


and the positive pole at the other, the luminous phenomena seem to depend more on the positive than on the negative at the ordinary exhaustion hitherto used to get the best phenomena of vacuum tubes. But at a very high exhaustion the phenomena noticed in ordinary vacuum tubes when the induction spark passes through them, — an appearance of cloudy luminosity and of stratifications, — disappear entirely. No cloud or fog whatever is seen in the body of the tube, and with such a vacuum as is used in these experiments the only light observed is that from the phosphorescent surface of the glass. Figure 458

represents two bulbs, alike in shape and position of poles, the only difference being that one is at an exhaustion equal to a few millimetres of mercury, — such a moderate exhaustion as will give the ordinary luminous phenomena, — whilst the other is exhausted to about the millionth of an atmosphere. First connect the moderately exhausted bulb *A* with the induction coil, and make the pole at one side, *a*, always negative, and the other poles with which the bulb is furnished positive in succession. As the position of the positive pole is changed, the line of violet light joining the two poles changes, the electric current always choosing the shortest path between the two poles, and moving about the bulb as the position of the wires is altered.

Try the same experiments with the highly exhausted globe *B*. Make *a′* the negative pole, as before. This pole has a concave surface. The molecular rays will cross in the centre of the bulb, and, diverging thence, will fall on the opposite side, producing a circular patch of green phosphorescent light. The position of the spot of light remains the same whether *b*, *c*, or *d* is made the positive pole. In a very high vacuum, no matter what may be the position of the positive pole, the radiant matter always darts off in straight lines from the negative pole, the rays being always perpendicular to the surface.

Fig. 459.



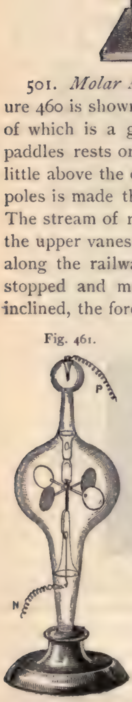
500. *Shadows cast by Radiant Matter.* — In Figure 459 is shown a pear-shaped vacuum tube with the negative pole *a* at the small end. In the middle of the tube is an aluminium cross *b*. The molecular rays from *a* which reach the opposite end of the tube develop phosphorescence, but a portion of the rays are intercepted by the cross, whose shadow is seen on the end of

the tube. The portion of the end of the tube behind the cross is shielded from the molecular blows, and so remains dark.

Fig. 460.

501. *Molar Motion produced by Radiant Matter.* — In Figure 460 is shown a highly exhausted vacuum tube, in the centre of which is a glass railway. A little wheel with broad mica paddles rests on this railway. At each end of the tube and a little above the centre there is an aluminium pole. One of the poles is made the negative terminal and the other the positive. The stream of radiant matter from the negative terminal strikes the upper vanes of the little paddle-wheel and causes it to roll along the railway. On the reversal of the poles, the wheel is stopped and made to reverse its path. If the tube is gently inclined, the force of the radiant stream is seen to be sufficient to drive the wheel up hill.

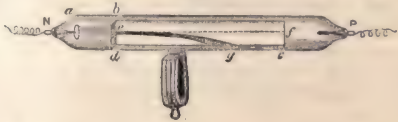
Fig. 461.



In Figure 461 is shown a little fly in the centre of a highly exhausted bulb. The fly consists of four arms of aluminium, each carrying at the end a thin aluminium disc, coated on one side with mica. The fly turns upon a hard steel point, which is connected with the negative pole of the induction coil. The positive terminal is at the top of the bulb. With a pressure of only a few millimetres, a halo of velvety violet light settles on the metallic sides of the discs, the mica sides remaining dark. As the pressure diminishes, a dark space separates the violet halo from the metallic disc. With a pressure of half a millimetre, the dark space extends to the glass, and the fly begins to rotate, the metallic discs moving

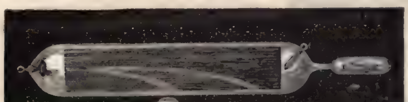
backward. As we continue the exhaustion, the dark space widens out and appears to flatten itself against the glass. The rotation now becomes very rapid. The fly is turned by the reaction of the molecules as they are shot from the discs.

Fig. 462.



502. *Deflection of Radiant Matter by a Magnet.* — In Figure 462 is shown a highly exhausted tube with its negative terminal at *N* and its positive terminal at *P*. There is a long phosphorescent screen *b c* passing down the centre of the tube. In front of the negative pole is a mica plate *b d* with a hole *e* in its centre. On turning on the electric current, a line of phosphorescent light is seen along the screen in the direction *e f*. This line of light reveals the path of the radiant stream. A powerful horseshoe magnet is now placed under the tube, and the line of light, *e g*, becomes curved under the magnetic influence, waving about like a flexible wand as the magnet is moved to and fro.

Fig. 463.



"This action of the magnet is very curious, and, if carefully followed up, will elucidate other properties of radiant matter. Figure 463 represents a tube exactly similar, but, having at one end a small potash tube, which, if heated, will slightly injure the

vacuum. When the induction current is turned on, the ray of matter is seen tracing its trajectory in a curved line along the screen, under the influence of the horseshoe magnet beneath. Let us observe the shape of the curve. The molecules shot from the negative pole may be likened to a discharge of iron bullets from a mitrailleuse, and the magnet beneath will represent the earth curving the trajectory of the shot by gravitation. The curved trajectory of the shot is accurately traced on the luminous screen. Now suppose the deflecting force to remain constant, the curve traced by the projectile varies with the velocity. If more powder is put in the gun, the velocity will be greater and the trajectory flatter ; and if a denser resisting medium is interposed between the gun and the target, the velocity of the shot will be diminished, and it will move in a greater curve and come to the ground sooner. The velocity of this stream of radiant molecules cannot well be increased by strengthening the battery, but they can be made to suffer greater resistance in their flight from one end of the tube to the other. In the experiment shown, the caustic potash is heated with a spirit lamp, and so a trace more of gas is thrown in. Instantly the stream of radiant matter responds. Its velocity is impeded, the magnetism has longer time in which to act on the individual molecules, the trajectory becomes more and more curved until, instead of shooting nearly to the end of the tube, the 'molecular bullets' fall to the bottom before they have got more than half-way."

Fig. 464.

503. *Development of Heat by Radiant Matter.* — The bulb (Figure 464) is furnished with a negative pole in the form of a cup *a*. The rays will therefore be projected to a focus on a piece of iridio-platinum *b* supported in the centre of the bulb. The induction coil is first slightly turned on so as not to bring out its full power. The focus plays on the metal, raising it to a white heat. By bringing a small magnet

near it the focus of heat may be deflected. By shifting the magnet we can draw the focus up and down, or completely away from the metal, so as to leave it non-luminous. When we withdraw the magnet so as to let the molecules have full play again, the metal becomes white-hot. When we increase the intensity of the spark, the iridio-platinum glows with almost insupportable brilliancy, and at last melts.

504. *The Radiometer.* — The ordinary ***radiometer*** is similar in construction to the instrument shown in Figure 461. The discs of the fly are of mica blackened on one side. The fly is usually supported on a glass stem. The bulb is highly exhausted. When the radiometer is placed in the light, the fly begins to rotate, the blackened surfaces of the discs moving backward. The more intense the light, the more rapid the rotation. The rotation is due to the action of radiant matter. The blackened sides of the discs absorb the radiation better than the light ones. They thus become more heated, and repel the molecules with greater energy. The reaction of the projected molecules is therefore greater on the blackened sides of the discs. This excess of reaction causes the rotation.

It has been suggested that the ether itself may be merely a form of radiant matter, and that light and heat may be propagated through it by molecular projection.

VII.

METEOROLOGY.

I.

CONSTITUTION OF THE ATMOSPHERE.

505. *The Term Meteorology.* — The term *meteor* was formerly applied to any natural phenomenon occurring within the limits of the atmosphere; hence the term *meteorology* as applied to that branch of Natural Philosophy which treats of the atmosphere.

506. *The Composition of the Atmosphere.* — The atmosphere is composed chiefly of oxygen and nitrogen in a state of mechanical mixture, and not of chemical combination. In every 100 volumes of air there are nearly 79.1 volumes of nitrogen and 20.9 volumes of oxygen. Owing to the tendency of these two gases to diffuse into each other, and to the currents which exist in the atmosphere, these proportions are sensibly the same in all parts of the globe and at all accessible elevations above its surface.

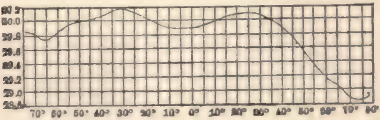
In addition to the oxygen and nitrogen, the atmosphere contains also a little carbonic acid and watery vapor. The amount of carbonic acid varies, in the open country, from 4 to 6 parts in a thousand. The amount of moisture is very variable, ranging from 4 parts in one hundred to 1 part in a thousand.

507. *The Height of the Atmosphere.* — The atmosphere

is held to the earth by gravity, and it must terminate at that height at which the attraction of the earth is balanced by the repulsion of the particles of the air. At the height of 50 miles the atmosphere is wellnigh inappreciable in its effect upon twilight. The phenomena of lunar eclipses indicate an appreciable atmosphere to the height of 66 miles; while the phenomena of shooting stars and of the auroral light show that an appreciable atmosphere exists at the height of 200 or 300 miles, and probably of more than 500 miles, above the earth's surface.

508. *The Weight of the Atmosphere.* — The weight or downward pressure of the air at any point is ascertained by the use of the barometer. It is found to be different at different parts of the earth, and to be in a state of constant fluctuation at the same place. If we observe the height of the barometer every hour of the day, and then divide the sum of the observed heights by 24, we obtain the *mean height for the day.* By dividing the sum of the daily means for a month by the number of days in the month, we obtain the *mean height for the month.* By dividing the sum of the monthly means for a year by 12, we obtain the *mean height for the year.* If we divide the sum of the annual means for a series of years by the number of years in the period, we obtain the *mean height of the barometer* for the place of observation. This at Boston is 29.988 inches.

Fig. 465.

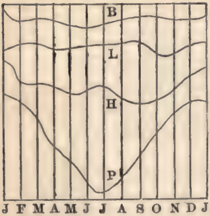


509. *The Mean Height of the Barometer at Different Latitudes.* — The curve in Figure 465 shows the mean height of the barometer at different latitudes from 80°

north to 80° south. The numbers at the bottom show the latitude, and those at the side the height of the barometer in inches. The height at which the curve crosses the vertical lines of the diagram shows the mean height of the barometer at that latitude. The height is found by following the horizontal lines to the left; and the latitude, by following the vertical lines to the bottom. It will be seen from the diagram, that the mean height of the barometer is greatest at 32° north and 25° south of the equator, and lowest at 64° north and about 70° south of the equator; also that the mean height of the barometer is generally greater north of the equator than south of it. There is a belt of low pressure at the equator.

510. *The Mean Height of the Barometer for Different Months.* — The mean height of the barometer varies somewhat from month to month during the year, being generally higher in winter than in summer. In many places the mean height in winter exceeds that of summer by half an inch, while in other places the inequality almost entirely disappears. At Pekin, China, the mean height of the barometer for January exceeds that for July by three quarters of an inch. Throughout a considerable portion of the continent of Asia the winter mean is considerably above that for the summer. In the middle latitudes of Europe and America the mean height of the barometer is usually about the same for each month of the year. At Boston the mean pressure does not differ more than one tenth of an inch for any two months of the year. The same is true of London and Paris. The four curves *B*, *L*, *H*, and *P* (Figure 466) show the monthly fluctuations of the mean

Fig. 466.

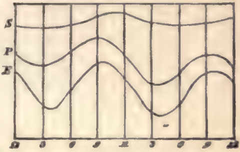


pressure at Boston, London, Havana, and Pekin. The spaces and letters at the bottom of the line represent the months, and the vertical lines the height.

511. *Hourly Fluctuation of the Barometer.* — When the indications of the barometer for each hour of the day for a long period are averaged, it will be found that these averages are not equal to each other. The height of the barometer is greatest about 10 A.M. and least at about 4 P.M. There are also smaller fluctuations at night, the barometer attaining a second maximum at about 10 P.M., and a second minimum at about 4 A.M. This diurnal oscillation is greatest at the equator, and decreases as we approach either pole.

At the equator it is 0.104 inch; in latitude 40° it is 0.05 inch; and in latitude 70° it is only 0.003 inch. The three curves of Figure 467 show the hourly variation of pressure at the equator, *E*, at Philadelphia, *P*, and at St. Petersburg, *S*. The numbers at the bottom indicate the hours of the day.

Fig. 467.



512. *Fluctuation depending on the Position of the Moon.* — There is a small fluctuation of the barometer depending on the position of the moon, but this variation is exceedingly minute and can be detected only by taking the mean of the most accurate observations continued for a long time. These fluctuations indicate a feeble tide in the atmosphere similar to those of the ocean.

513. *Irregular Fluctuations.* — The irregular fluctuations of the barometer are far greater than the periodic ones. In the middle latitudes the barometer is almost constantly in motion, and these fluctuations are so great and so irregular as in great measure to conceal the periodic movement. It is only by taking the mean of a long series of observa-

tions that the latter can be detected at all. The difference between the greatest and least heights of the barometer for a single month is called the *monthly oscillation*, and by combining observations extending over a series of years we obtain the *mean monthly oscillation*. The mean monthly oscillation is least at the equator, and increases as we proceed towards the poles.

At the equator it is about $\frac{1}{10}$ of an inch; in latitude 30° it is $\frac{4}{10}$ of an inch; in latitude 45°, over the Atlantic Ocean, it is 1 inch; in latitude 65° it is $1\frac{1}{3}$ inches. During the three winter months the mean monthly oscillation is about $\frac{1}{3}$ greater than the numbers given above. These oscillations are generally less over the continents of Europe and America than over the Atlantic Ocean on the same parallel. The extreme fluctuations of the barometer are much greater than the mean monthly oscillations. The greatest and least observed heights of the barometer at Boston are 31.125 inches and 28.47 inches, the difference being 2.655 inches. The greatest observed difference at London is 3 inches; and at St. Petersburg, 3.5 inches.

II.

TEMPERATURE OF THE ATMOSPHERE.

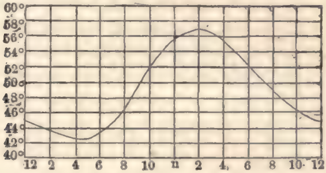
514. *How the Atmosphere becomes Heated.* — The atmosphere becomes heated partly by absorbing the direct rays of the sun, partly by contact with the warmer earth, and partly by absorbing the obscure heat radiated from the earth.

A portion of the heat emitted by the sun is absorbed by our atmosphere before it can reach the earth's surface. It is estimated that on a clear day our atmosphere absorbs about one fourth of the rays which traverse it vertically. The heat thus absorbed raises the temperature of the

atmosphere. It is mainly the obscure rays that are absorbed by the atmosphere, and this absorption is done chiefly by the watery vapor in the atmosphere. The rays of the sun which reach the earth's surface are absorbed by it. The surface thus becomes heated, and communicates heat to the air which rests upon it. This heated air, becoming lighter through expansion, rises and gives place to colder air from above, which in turn becomes heated by contact with the earth.

As the surface of the earth becomes warmed by the direct rays of the sun, it radiates obscure heat back into the atmosphere. These rays are partially absorbed by the atmosphere, especially in the lower layers, where watery vapor is most abundant.

Fig. 468.



515. *Hourly Variations of Temperature.* — The temperature of a place varies from hour to hour according to the elevation of the sun above the horizon. The average of observations taken for a long period shows that the mean hourly variations of temperature are extremely regular. The curve in Figure 468 shows the mean hourly variations of temperature at New Haven. There is a maximum and minimum of temperature each day, the minimum occurring about an hour before sunrise, and the maximum about two hours after noon.

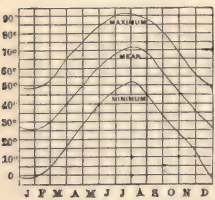
The highest temperature of the day, other things being

equal, occurs when the amount of heat lost each instant by radiation is just equal to that received from the sun. Before midday the earth receives more heat from the sun than it loses by radiation, and the temperature rises. After noon the earth receives, each instant, less heat from the sun than it did at noon; but for some time it still receives heat faster than it parts with it. Hence the maximum of temperature occurs some time after noon. During the night we receive no direct heat from the sun, and the earth cools by radiation. About an hour before sunrise the heat received from the returning sun becomes equal to that lost by radiation, and the temperature ceases to fall.

516. *Mean Temperature of a Day.* — The mean temperature of a day is the average temperature of the 24 hours. This might be found by observing the temperature each hour of the day, and dividing the sum of these observed temperatures by 24. This method is very laborious. In practice, the mean temperature of the day is found by taking the average of three observations, one at 6 A. M., one at 2 P. M., and one at 9 P. M.

517. *Monthly Variations of Temperature.* — The curves of Figure 469 show the mean temperature and also the mean maximum and minimum temperature for each month of the year at New Haven, according to observations extending through 86 years. The months are given on the horizontal line at the bottom, and the degrees of temperature on the vertical line at the left. The warmest months of the year for this place are July and August, the maximum occurring about the 24th July. The coldest month is January, the minimum occurring about the 21st of this month. The difference

Fig. 469.



between the maximum and minimum temperature is greater for the cold than for the warm months.

The chief reasons why it is colder during the winter months than during the summer months are that the sun is farther from the zenith and is a shorter time above the horizon.

The earth is receiving the most heat from the sun at the time of the summer solstice, but the temperature continues to rise as long as the earth receives more heat from the sun during the day than it loses by radiation during the night. During the autumn the loss at night is much greater than the gain by day, and the temperature rapidly falls. The temperature continues to fall till the gain by day is again equal to the loss by night. This does not occur till some time after the winter solstice.

518. *Irregular Fluctuations of Temperature.* — Besides the periodic variations of temperature, there are constant irregular fluctuations of temperature. These are liable to occur any hour of the day and any day of the year.

519. *Variations of Temperature with the Latitude.* — As we proceed from the equator to the poles, the temperature generally falls, but not at a uniform rate, and the rate of fall will be different on different meridians. Hence the lines of equal temperature on the surface of the earth do not coincide with the parallels of latitude. Lines which connect places of equal mean temperature are called *isothermal lines.* The isothermal lines for every ten degrees are shown on the accompanying map (Figure 470). These lines show the general distribution of heat over the surface of the earth. They are seen to be much more irregular on and around the continents than in the oceans.

520. *The Temperature of the two Sides of the Atlantic.* — It will be seen from the map in Figure 470 that the mean temperature of the eastern side of the Northern Atlantic Ocean is considerably higher than that of the western side

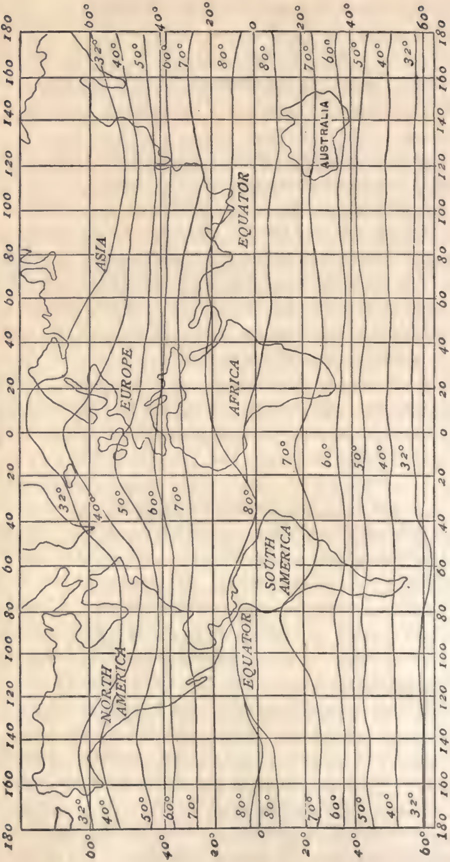

ASIA
EUROPE
AFRICA
AUSTRALIA
EQUATOR
NORTH AMERICA
SOUTH AMERICA
EQUATOR
32°
40°
50°
60°
70°
80°

Fig. 470.

at the same latitude. The temperature of Dublin is as high as that of New York, though the former is 13° farther north, while near Lake Superior, in latitude 50°, we find the same mean temperature as at the North Cape, in latitude 72°.

The high temperature of the European coast is due to the high temperature of the Northern Atlantic and the prevalent westerly winds. The Gulf Stream conveys the warm water of the equatorial region into the North Atlantic. The temperature of the North Atlantic is thus raised considerably above what is due to its latitude, and the prevalent westerly winds of the middle latitudes carry this heat to the eastern side of the Atlantic and away from its western side.

521. *The Temperature of the two Sides of the Pacific.* — Owing to the currents of the Pacific Ocean, there is a corresponding difference of temperature between its eastern and western coast, the temperature of the east coast being higher than that of the west. This causes a marked difference of temperature between the eastern and western coasts of North America at places on the same parallel. The same isothermal line will be found 10 or 15 degrees farther north on the Pacific coast of North America than on the Atlantic coast.

522. *The Temperature of the Northern and Southern Hemispheres.* — The mean temperature of the northern hemisphere is nearly three degrees higher than that of the southern hemisphere.

The unequal temperature of the two hemispheres is probably due to the unequal distribution of land and water. The northern hemisphere contains more land and less water than the southern. In the southern hemisphere the sun's rays fall chiefly upon water, and a large amount of heat is consumed in the evaporation of water. In the condensation of vapor the heat is again liberated.

Observations show that there is more condensation in the northern hemisphere than in the southern. Thus the southern hemisphere is cooled more by evaporation and warmed less by condensation than the northern hemisphere.

523. *Mean and Extreme Temperatures of a Place.* — Two places having the same mean temperature may differ greatly in their extreme temperatures. New York and Liverpool have the same mean temperature, but the difference between the mean temperature of the three summer months and that of the three winter months is twice as great in New York as in Liverpool.

In some localities the mean temperature of the hottest month of the year is less than 5° above that of the coldest, while in other localities it is 70° or 80° above.

524. *Marine and Continental Climates.* — The temperature of water changes less than that of land. The specific heat of water being much higher than that of land, a much greater amount of heat is consumed in raising the temperature of an equal mass of water the same number of degrees, and a much greater amount of heat is liberated in the cooling of an equal mass of water. Hence when land and water are receiving or losing heat at the same rate, the temperature of the former will rise higher or fall lower than that of the latter in the same time. The high latent heat of watery vapor tends to keep the temperature of water uniform, a large amount of heat being rendered latent by evaporation when the temperature is rising, and an equally large amount being liberated by condensation when the temperature is falling. Again, the sun's rays penetrate water to a greater depth than land, and at the same time the currents in the ocean tend to equalize the temperature of the water at different depths. Hence while land becomes heated only at the surface, water becomes heated to a considerable depth below the

surface. The greater depth of water heated and cooled as the temperature rises and falls would cause the temperature to change less at the surface of water than of land.

When the temperature of a place is controlled mainly by the ocean, the temperature is equable, and the climate is called *marine;* when, on the contrary, it is controlled mainly by the continent, the temperature is extreme, and the climate is called *continental.* On the eastern coast of the United States, where the prevalent winds are from the land, there is a great annual range of temperature and a continental climate; while in the western part of Europe, where the prevalent winds are from the ocean, the temperature is more uniform and the climate marine.

525. *Change of Temperature with the Elevation.* — As we ascend in the atmosphere from the earth, the temperature falls. The rate of decrease varies with the latitude of the place, with the time of the year, and with the hour of the day. It is more rapid in warm countries than in cold, and in the hot months than in the cold. It is most rapid about 5 P. M., and least rapid about sunrise. The change is also most rapid near the earth, and decreases as we ascend.

There are two main reasons why the temperature of the atmosphere falls as we ascend: (1) The air of the earth's surface becomes heated and expanded, and tends to rise because of its diminished specific gravity. As the air ascends it meets with less pressure, and therefore expands; this expansion consumes heat, and causes the temperature to fall. (2) The moisture in the air becomes less and less as we ascend, and hence there is less absorption of the solar rays, and it is only the rays which are absorbed that tend to raise the temperature; also there will be less hindrance to the escape into space of the heat radiated from the atmosphere.

526. *The Line of Perpetual Snow.* — Since the tempera-

ture of the atmosphere falls as we ascend, the tops of high mountains, even within the tropics, are covered with perpetual snow. The snow-line depends more upon the temperature of the hottest month than upon the mean temperature of the year. It is not therefore the line whose mean temperature is 32°. It depends also to a considerable extent upon the annual snow-fall.

Under the equator the height of the snow-line varies from 15,000 to 16,000 feet, where the mean annual temperature is 35°. On the Alps the average height of the snowline is 8800 feet, where the mean annual temperature is 25°; while on the coast of Norway its height is only 2400 feet, where the mean annual temperature is 21°.

527. *The Atmosphere a Regulator of Temperature.*— During the day the atmosphere absorbs a portion of the sun's rays, so that they are less excessive on reaching the earth. A considerable portion of the heat thus absorbed during the day is rendered latent by expansion. At night the air intercepts a part of the rays emitted by the earth, and so keeps the heat from escaping into space. At the same time, as the air is cooled, it contracts, and so liberates the heat that was rendered latent by expansion during the day. Were it not for the atmosphere the days would be very much hotter and the nights very much colder than they are now. It is chiefly by means of the watery vapor present in the atmosphere that it acts thus as a regulator of temperature.

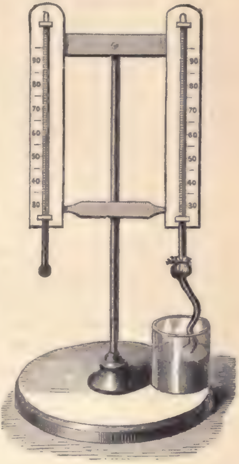
III.

HUMIDITY OF THE ATMOSPHERE.

528. *The Hygrometer.*—An instrument capable of measuring the moisture of the air is called a *hygrometer.* A *hygroscope* is an instrument which merely shows that there

are changes of moisture, without being capable of measuring the amount of moisture present. The hygrometer shown in Figure 471 is one of the most convenient and accurate in use. It is known as *Mason's hygrometer*. It consists of two thermometers. The bulb of one of these is kept moist by being covered with muslin or silk, the fibres of which dip into a reservoir of water. The water is drawn up to the bulb by capillary action, and the evaporation from its surface lowers its temperature. Hence the wet-bulb thermometer will always show the lower temperature. The greater the difference of reading between the two thermometers, the faster the evaporation from the wet bulb and the drier the air.

Fig. 471.



529. *Humidity of the Air.* — The amount of moisture which a cubic foot of air can hold increases with the temperature. When the air contains all the moisture it can hold at that temperature, it is said to be *saturated* with moisture. By the *humidity* of the air we do not mean the absolute amount of moisture in it, but its degree of saturation. If the air is half saturated, its humidity is 50; if three-quarters saturated, 75; etc.

530. *Dew-Point.* — The *dew-point* is the temperature at which the air would become saturated with the moisture in it, and its moisture begin to be deposited as dew. It is not a fixed temperature, like those of the freezing and boil-

ing points, but varies with the temperature and humidity of the air. The greater the humidity of the air, the less the temperature would have to fall to reach the dew-point.

From the reading of the two thermometers in Mason's hygrometer, it is possible to calculate the temperature of the dew-point, the humidity of the air, and the number of grains of moisture in a cubic foot of air. Tables are prepared to be used with this instrument in which the results of these calculations are given for different readings of the thermometers.

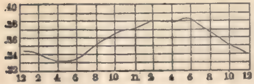
The difference between the temperature of the dew-point and that of the air is called the *complement of the dew-point.* The drier the air, the greater the complement of the dew-point.

In ordinary pleasant weather the complement of the dew-point is from 10° to 15°. Occasionally, at Philadelphia, it amounts to 25° or 30°, and has been observed as high as 45°. In India it has been known to reach 61°, and in California 78°. In the last case the atmosphere would contain only 6 per cent of the vapor required for its saturation.

531. *Diurnal Variation in the Vapor present in the Atmosphere.* — The amount of vapor present in the atmosphere is subject to great fluctuations, some of which are irregular and others periodic. As a rule, the amount of vapor in the atmosphere is least about an hour before sunrise, and greatest just before sunset, the mean diurnal variation amounting to about ⅛ of the average amount of vapor present.

The curve in Figure 472 shows the diurnal variation at Philadelphia, the figures at the left indicating the pressure of the vapor in inches of mercury, at the hours given at the bottom. This diurnal variation in the amount of vapor is due to the

Fig. 472.



diurnal change in temperature. As the temperature rises during the day, more water is evaporated from the ocean and the moist earth, and the amount of vapor in the air increases. During the night a portion of the vapor is condensed in the form of dew and hoar-frost, and the amount of vapor present in the air decreases.

532. *Annual Variation in the Amount of Vapor present in the Atmosphere.* — In the northern hemisphere the mean amount of vapor present in the atmosphere is greatest in July, when the mean temperature is highest, and least in January, when the mean temperature is lowest. This is due to the more rapid evaporation in summer than in winter.

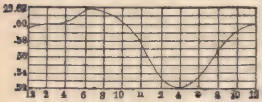
533. *Variation in the Amount of Vapor with the Elevation.* — The humidity of the atmosphere as a rule decreases as we rise above the earth, though there is a slight increase of humidity for the first 3000 feet. At the highest elevations at which observations have been taken the air has never been found entirely free from moisture.

534. *Diurnal Variation of the Pressure of the Gaseous Atmosphere.* — The earth is really enveloped in two atmospheres, one of vapor and one of permanent gases. These two atmospheres are mixed together, and by their combined pressure cause the rise of the barometer. Other things being equal, the greater the amount of vapor present in the atmosphere the higher the barometer, and vice versa. Fluctuations in the height of the barometer are caused by changes in the temperature of the air and the amount of vapor present in the atmosphere. A diminution of vapor and an increase in temperature both tend to cause the barometer to fall.

If we subtract the pressure of the vapor in the atmosphere from that of the whole atmosphere, the remainder will be the pressure of the gaseous atmosphere. When this deduction from the total pressure has been made, it is

found that at Philadelphia the pressure of the gaseous atmosphere is greatest at about an hour after sunrise and least about 4 P. M., as is shown by the curve of Figure 473.

Fig. 473.



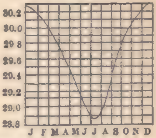
This fluctuation of the pressure of the gaseous atmosphere is evidently due to the variation of solar heat. As the heat of the day increases, the atmosphere becomes warmed, expands, and swells up to a height greater than it had at night. The upper portion therefore flows off laterally in all directions to places where the height of the atmosphere is less, owing to a lower temperature. This overflow diminishes the amount and pressure of the air at the place *from* which it takes place, and increases the amount and pressure of the air at the place *towards* which the overflow proceeds. The outflow increases with the temperature, and continues awhile after the hottest part of the day is passed. Hence the pressure continues to decrease for some time after the hottest part of the day. As the temperature falls at night, the air again contracts, and its depth becomes less than during the day, and the depression thus produced gives rise to an inflow, which increases the amount and pressure of the air. This inflow of air and increase of pressure continue for some time after the coldest part of the day is past.

The pressure of the vapor and that of the gaseous atmosphere have each but one maximum and minimum a day. Their maxima and mimima do not, however, coincide, but occur at nearly opposite hours in the day. The combination of these two pressures gives two maxima and two minima in the resulting pressures.

535. *Annual Variation of the Pressure of the Gaseous Atmosphere.* — In the northern hemisphere the pressure of the gaseous atmosphere is greatest in January, when the

temperature is lowest, and least in July, when the temperature is highest. The difference between the summer and winter pressures of the gaseous atmosphere is very unequal in different countries. In the eastern part of the United States this difference amounts to about half an inch, while in Central Asia it amounts to above an inch, and at the equator is scarcely appreciable. Figure 474 shows the annual curve of pressure at Pekin, China.

Fig. 474.



The annual fluctuation in the pressure of the gaseous atmosphere is due to the annual variation in temperature, and the amount of the fluctuation increases with the annual range of temperature. During the summer the air expands and overflows, and the pressure falls. During the winter the contraction of the air gives rise to an inflow and an increase of pressure.

In the temperate zones of Europe and America the increase in the amount of vapor in the atmosphere nearly balances the loss of weight sustained by the gaseous atmosphere, so that the pressure of the whole atmosphere remains about the same throughout the year.

IV.

MOVEMENTS OF THE ATMOSPHERE.

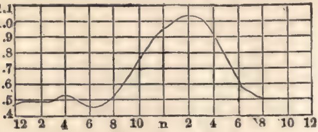
536. *Winds.* — Wind is air in motion. Although the winds are proverbially variable and fickle, they are governed by laws as fixed and definite as those which regulate the temperature and pressure of the atmosphere.

The force of a wind may be indicated either by its velocity in miles per hour or by its pressure in pounds per square foot. The character, velocity, and pressure of various winds are given in the following table, taken from Loomis: —

Character.	Velocity in Miles per Hour.	Force in Pounds per Square Foot.
Just perceptible	2	0.02
Gently pleasant	4	0.08
Pleasant brisk	12½	0.75
Very brisk	25	3.00
High wind	35	6
Very high wind	45	10
Strong gale	60	18
Violent gale	70	24
Hurricane	80	31
Most violent hurricane	100	49

From a long series of observations at Philadelphia it appears that the mean velocity of the wind is 11 miles an hour. The mean velocity varies somewhat during the day and during the year. It is least about sunrise and greatest about 2 P. M. It is nearly uniform during the

Fig. 475.



night. The curve in Figure 475 shows this diurnal variation in the force of the wind, the figures in the vertical line indicating the pressure of the wind in pounds per square foot.

According to the observations at Philadelphia, the mean velocity of the wind is 9 miles per hour in summer and 14 miles in winter. The mean velocity varies somewhat in different parts of the globe, but within rather narrow

limits. The mean velocity at sea appears to be about 18 miles per hour.

537. *Cause of Winds.* — Movements of the atmosphere are produced either by the unequal pressure of the atmosphere at different points, or by the unequal specific gravity of different portions of the atmosphere.

Surface currents will always set in *from* a region of high pressure *towards* a region of low pressure.

Unequal specific gravity of the air may be due to inequalities of temperature or of humidity. Suppose the surface of the earth in the neighborhood of *C* (Figure 476) to become excessively heated. The air above *C* will by expansion become lighter than the surrounding air. This lighter air will accordingly rise, and its place will be supplied by an inflow along the surface from every side. At the same time the heated column, rising above the surrounding atmosphere, gives rise to an outflow at the top. At a certain distance from the heated column there will be descending currents to supply the place of the air which is flowing in towards the heated region at the surface of the earth.

Fig. 476.

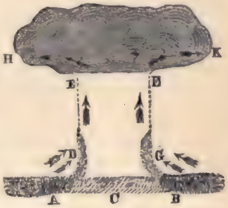


Fig. 477.

The system of currents that would be developed on every side of an excessively heated region is shown in Figure 477, the arrows indicating the direction of the currents. A system of currents in just the opposite direction would be developed on every side of an excessively cold region.

The specific gravity of the vapor of water is only about two thirds that of dry air. As it takes time for the vapor to diffuse itself into the atmosphere, an excess of aqueous vapor tends to produce a region of low specific gravity, and so to develop a system of currents similar to those developed by a region of high temperature.

Were the barometer everywhere to indicate the same pressure at the surface of the earth, the wind at the surface would still blow *from* a region of low temperature *to* a region of high temperature, and *from* a region of little vapor *to* a region of excessive vapor.

538. *The Direction of the Winds modified by the Rotation of the Earth.* — The earth's rotation from west to east in 24 hours is on an axis perpendicular to its equator. Every point on the earth's surface is carried around in the same time, but points near the equator describe longer paths, and hence must move with greater velocity than those near the poles. The velocity of rotation at the surface is greatest at the equator and decreases towards the poles. At the equator it is 1036 miles per hour; 15° from the equator it is 1000 miles per hour; 30° from the equator, 897 miles; 45° from the equator, 732 miles; 60° from the equator, 518 miles; 75° from the equator, 268 miles.

If a mass of quiescent air from parallel 30° were suddenly transported to parallel 15°, it would have an easterly motion of 103 miles an hour *less* than that of the parallel arrived at. It would therefore seem to be moving over the surface of the earth westward at the rate of 103 miles an hour. Of course it would really be the surface of the earth which would be moving under it eastward at that rate. The effect upon bodies on the surface of the earth would be the same as if the earth was stationary, and the wind blowing over it to the west at the above rate.

If, on the other hand, a mass of quiescent air were suddenly transported from parallel 15° to parallel 30°, it would have an easterly motion of 103 miles an hour *greater* than the parallel arrived at.

In general, any wind blowing *towards* the equator is deflected towards the *west* by the rotation of the earth, so as to make it an *easterly* wind; and any wind blowing *from* the equator is deflected towards the *east* by the rotation of the earth, so as to make it a *westerly* wind.

The rotation of the earth deflects every wind north of the equator towards the *right* of an observer looking in the direction towards which the wind blows; and every wind south of the equator, towards his *left*.

539. *System of Winds.* — There are three great systems of winds upon the globe, namely, the *trade-winds*, the *middle-latitude winds*, and the *polar winds*.

540. *Trade-Winds.* — There is a belt of excessively heated air surrounding the earth within the tropics. This heated air develops a system of currents on each side of it, similar to those described in section 537. Surface currents set in *towards* the equator *from* the north and the south, and upper currents *from* the equator *towards* the north and the south. The rotation of the earth deflects the surface currents towards the west, so as to make them *easterly* winds; and the upper currents towards the east, so as to make them *westerly* winds. The trade-wind north of the equator is a *northeast* wind, and that south of the equator is a *southeast* wind.

In the Atlantic Ocean the northeast trades extend on an average from about 7° north of the equator to about 29°; while the southeast trades extend about 20° south of the equator. Between these two trades there is a belt of calms or variable winds, varying at different seasons from 150 to 500 miles in breadth. The centre of this belt is about 5° north of the equator.

The trades, with their intervening belt of calms, move northward in summer and southward in winter. In the spring the centre of the belt of calms is only 1° or 2° north of the equator, while in summer it is 9° or 10° north of the equator.

541. *Cause of the High Barometer near the Parallel of 32°.* — As the upper equatorial currents move towards the poles they tend to increase the pressure of the atmosphere towards the north and the south; for since the meridians converge as we proceed from the equator towards the poles, the air as it moves towards the poles must increase in depth, and so produce a greater pressure at the surface. The distance between the meridians is nearly one sixth less in latitude 32° than at the equator. This increased pressure of the air in middle latitudes arrests the farther progress of the polar current, and a calm ensues. The upper air descends to the earth's surface, and joins the surface current towards the equator, where it again ascends, and thus maintains a perpetual circulation.

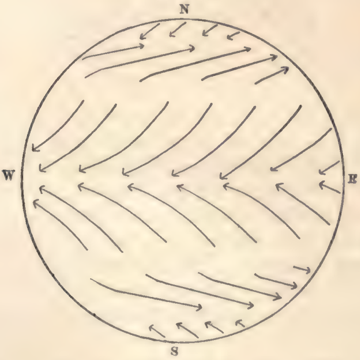
542. *The Middle-Latitude Winds.* — The high pressure near the parallel of 32° gives rise to surface currents from the equator towards the poles, in opposition to the tendency of the increasing density of the air due to the diminution of the temperature as we proceed towards the poles, and to upper currents from the poles towards the equator. The surface currents are deflected by the rotation of the earth towards the east, so as to make them westerly winds; and the upper currents towards the west, so as to make them easterly winds. These surface currents are the prevailing winds of the middle latitudes. In the northern hemisphere they blow from a point a little south of west, and in the southern hemisphere from a point a little north of west. Throughout the middle latitudes of the United States the average direction of the wind is 10° south of west; and the easterly winds are to the westerly as 2 to 5. In corresponding latitudes in the

southern hemisphere, the prevalent direction of the surface winds is 17° north of west; and the easterly winds are to the westerly as 1 to 5.

These zones of westerly winds are from 25° to 30° wide. The westerly direction of the wind is most decided in the centre of the belt, and gradually diminishes as we approach the limit on either side.

543. *The Polar Winds.* — The extreme cold of the polar region produces the opposite effect to that of the extreme heat of the tropics. It produces great density of air, and develops surface currents blowing *from* the poles towards the equator, and upper currents in the opposite direction. These currents are deflected by the rotation of the earth, as in all other cases. The polar and middle-latitude winds encounter each other near the parallel of 60°.

Fig. 478.



The three systems of surface winds are shown in Figure 478, the arrows indicating the direction of the wind in each belt. Figure 479 shows the complete circulation of the atmosphere. There are reasons for supposing that

high up in the atmosphere the current continues uninterruptedly from the equator to the poles, as indicated by the upper arrows in Figure 480.

Fig. 479.

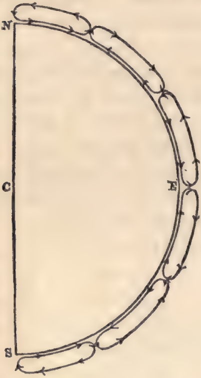
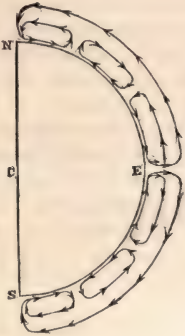


Fig. 480.



544. *Monsoons.* — During the summer months the surface of the land becomes heated to a higher temperature than that of the surrounding water, while during winter it becomes cooled to a lower temperature. Hence during the summer months there is a general tendency to develop surface winds from the oceans to the continents, and in the opposite direction during the winter months. This tendency may either give rise to winds in the direction in which it acts, or merely modify the direction and force of the prevailing winds.

In the former case we have what are called *monsoons*, that is, winds which blow during the summer months from the water to the land, and during the winter months from the land to the water. The most marked monsoons on the globe are those on the south coast of Asia, in the region

of the northeast trades. The tendency of the unequal heating of the continent of Asia and of the Indian Ocean during the winter months is to produce a wind in the direction of the trade-wind, and in the summer months in the opposite direction. The winter monsoon adds to the force of the trade-wind, while the summer monsoon overbalances the trade, and produces a wind in the opposite direction.

545. *Land and Sea Breezes.* — During the day the surface of the land becomes hotter than that of the neighboring water, and at night cooler. There is, therefore, a general tendency for the wind to blow from the water to the land during the day, and from the land to the water at night. When this tendency is strong enough to produce a wind in the direction in which it acts, we have what are called *land* and *sea breezes*, or winds blowing from the sea during the heat of the day, and from the land during the cool of the night. These winds are strongest on islands in tropical regions.

V.

CONDENSATION IN THE ATMOSPHERE.

A. Dew and Hoar-Frost.

546. *Origin of Dew.* — All bodies on the surface of the earth are radiating heat to the sky, and when they thus part with heat faster than they receive it, their temperature falls below that of the surrounding air. When the sun is above the horizon, they generally receive heat faster than they part with it by radiation, but at night they usually radiate heat faster than they receive it.

When the blades of grass, leaves of plants, and other objects on the surface of the earth become cooled by radiation below the dew-point of the atmosphere, they con-

dense upon themselves a portion of the atmospheric moisture in the form of dew. The greatest amount of dew is deposited upon the substances whose temperature becomes the lowest. Dew does not fall from the sky like rain, but collects upon those bodies which are cool enough to condense the vapor in the air in contact with them. A pitcher of ice-water, on a warm summer's day, becomes quickly covered with a film of dew, the cold surface of the pitcher condensing the vapor from the layer of air in contact with it.

547. *Circumstances favorable to the Formation of Dew.*— Anything which favors the loss of heat by radiation is favorable to the formation of dew.

A cloudless night and an unobstructed exposure to the sky are especially favorable to the formation of dew, because they allow the heat radiated by bodies to escape freely into space. A cloudy night or any artificial covering, however slight, prevents the formation of dew, for the clouds or coverings reflect back the heat radiated from the earth, and so keep bodies on its surface from cooling below the dew-point.

A slight breeze favors the formation of dew by renewing the air in contact with the surface as fast as it deposits its excess of vapor. A stiff breeze, however, prevents the formation of dew by allowing no layer of air to remain long enough in contact with the surface of a body to become sufficiently cooled to deposit its moisture. There is little dew on windy nights.

A moist atmosphere favors the formation of dew, because the more moisture in the air, the less the reduction of temperature at which the deposition of dew will begin. Good radiators and bad conductors receive the greatest amount of dew. The temperature of the surfaces of such bodies falls rapidly at night, because these surfaces lose heat rapidly by radiation and receive it slowly by conduction from

their interior or from the earth with which the bodies are in contact. Wool, being a good radiator and a poor conductor, collects a large amount of dew at night, while a plate of polished metal will receive scarcely any at all.

548. *Formation of Hoar-Frost.* — When the temperature of the surface is below the freezing-point, the moisture of the atmosphere is deposited upon it in the solid state, as *frost.* Hoar-frost is not frozen dew, but frozen vapor, that is, vapor deposited in the solid form without passing through the liquid state.

Since the leaves of plants sometimes become cooled by radiation several degrees below the air a few feet from them, it may happen that there will be a frost when the thermometer indicates a temperature of several degrees above the freezing-point. There is not, however, likely to be a frost unless the temperature of the dew-point is below 32°. The temperature of the surface will not fall much below the dew-point, because of the heat which is liberated on the deposition of the dew.

549. *Frost in Valleys.* — There is often sufficient frost in valleys and up to a certain height on the hillsides to kill plants, while higher up there is no frost at all. As the air on the hillsides is cooled by contact with the cold surface, it gradually settles into the valley, becoming cooler and cooler by contact with the surface as it descends, and raising the warmer air bodily out of the bottom of the valley, just as a heavy liquid will raise a lighter one by flowing under it. A thermometer attached to a high tower in a valley indicates at night the same average temperature as a thermometer on the hillside on the same level.

B. Fog and Mist.

550. *Origin of Fog.* — The watery vapor of the atmosphere is transparent, but when from any cause a portion

of the atmosphere becomes cooled below the dew-point, a part of the vapor becomes condensed into minute drops of water which float in the atmosphere. The partially condensed vapor becomes visible as a *mist* or *cloud*. When the condensation takes place near the surface of the earth it gives rise to a *fog* or *mist*.

When steam rises from a vessel of warm water and mixes with the colder air above, a portion of the vapor is condensed into a mist which is often improperly called steam. Steam proper is a *gaseous* body, while mist is a *liquid* body.

551. *Fogs over Rivers.* — At certain seasons of the year, and especially during the latter part of the summer, fogs form over rivers and lakes almost every clear and still night. During the night the air over the land becomes cooler than the water of the lake or river, and as the vapor rises from the water it is partially condensed by contact with the cooler air from the land, and gives rise to a fog which floats upon the surface of the water.

From the summit of Mount Washington, on a clear and quiet morning in August, one may trace the course of the Connecticut River by a long line of fog, and discover the position of a multitude of surrounding lakes by the patches of fog which rest upon them, while other portions of the country are entirely free from fog.

Such fogs usually disappear soon after sunrise, often rising and drifting away as clouds. Fogs are often formed in a similar manner over harbors and bays, and these fogs are frequently drifted inland by gentle currents of air. During the spring of the year fogs are sometimes formed over rivers where the water is colder than the surrounding air. In this case the moist air is chilled by contact with the cold water, and a portion of its vapor condensed into a fog.

552. *Fogs on the Breaking up of Frost.* — Extensive fogs

often occur in midwinter after a thaw or a warm rain. In this case warm and moist currents of air become chilled in passing over the cold surface of the frozen ground, and a part of the moisture is condensed as a fog. For a similar reason icebergs are liable to be enveloped in mist, the ice cooling the surrounding air sufficiently to condense a part of its moisture.

553. *Fogs on the Banks of Newfoundland.* — Fogs are prevalent along the northern side of the Gulf Stream, the warm and moist air over the Gulf Stream being chilled by contact with the colder air from the water on the north. These fogs are especially prevalent over the Banks of Newfoundland. These fogs occur every month of the year, but are especially frequent in the summer, when the Banks are enveloped in fog nearly half of the time. These Banks compel the cold arctic current at the bottom of the ocean to come to the surface, and the cold water thus brought to the surface chills the air laden with moisture from the Gulf Stream.

554. *Mist on the Tops of Mountains.* — The tops of mountains are liable to be enveloped in mist. The mountains compel the warm currents of air to rise to pass over them. As these currents rise they become chilled partially by expansion, and partially by contact with the cold surface of the mountains. When the air is chilled below its dew-point, a mist is formed, which is again dissipated as the air passes down into warmer regions on the other side of the mountains.

555. *How Fog is sustained in the Air.* — The particles of fog are sustained in the air in the same manner as a cloud of dust. The dust remains for a long time suspended in the air, although each particle may consist of matter two thousand times as dense as the air in which it floats. When the air is perfectly tranquil, these particles do indeed fall, but their descent is so slow that their

motion is perceptible only after a considerable interval of time.

556. *Indian Summer.* — "At certain seasons of the year there occurs a peculiar phenomenon called a *dry fog.* In the United States this frequently occurs in November, or the latter part of October, and this period is commonly known by the name of *Indian Summer.* It is characterized by a hazy condition of the atmosphere, a redness of the sky, absence of rain, and a mild temperature. This appears to result from a dry and stagnant state of the atmosphere, during which the air becomes filled with dust and smoke arising from numerous fires, by which its transparency is greatly impaired. A heavy rain washes out these impurities and effectually clears the sky.

"This phenomenon is not peculiar to the United States, a similar condition of the atmosphere being frequently observed in Central Europe. Moreover, this dry and stagnant state of the atmosphere is not limited to a single season of the year. The long periods of drought which frequently prevail in summer are characterized by a like condition of the atmosphere."

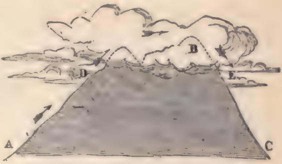
C. Clouds and Rain.

557. *Nature and Formation of Clouds.* — A cloud differs from a fog simply in its elevation above the earth. A fog might be defined as a cloud resting on the earth; and a cloud, as a fog floating in the air.

Clouds are formed whenever a mass of air away from the earth's surface is cooled below its dew-point. This cooling may be effected in various ways. A cold wind may penetrate a mass of warm air and cool it below its dew-point, or a warm moist wind may be cooled below its dew-point by penetrating a mass of cold air. Ascending currents of air are always cooled by expansion, and are very likely to give rise to clouds.

558. *Clouds on the Summits of Mountains.* — The summits of high mountains are usually enveloped in clouds even when the rest of the sky is clear. An interposed mountain forces a horizontal wind up to an unusual height where the temperature is low. When the temperature of the ascending current reaches its dew-point, a portion of its moisture is condensed as a cloud. Let $A\ B\ C$ (Figure 481) be a mountain interposed in the path of a horizontal current. The current will be forced upward, and made to glide along the side of the mountain. Let $D\ E$ represent the elevation at which the temperature of the ascending current will just reach its dew-point. As soon as the current passes above this line its vapor will be partially condensed so as to form a cloud, which will envelop the summit of the mountain. As soon as the current passes below the line $D\ E$ on the other side of the mountain, its temperature again rises above its dew-point, and the cloud is redissolved. The cloud is drifted by the wind, but is not blown away from the mountain because, as fast as it moves forward, a new cloud is formed behind it. Although the cloud on the mountain appears stationary, the particles which compose it are continually changing.

Fig. 481.



In a similar manner, even in tolerably level countries, the sky does not become overcast solely by clouds drifted by the wind from places beyond the horizon. The clouds are very often formed in sight of the observer. So too the sky often clears, not because the clouds are drifted off by the wind, but because they are dissipated by the increasing heat of the air.

559. *The Classification of Clouds.* — The four chief

varieties of clouds are the *cirrus*, the *cumulus*, the *stratus*, and the *nimbus*.

"The *cirrus* cloud consists of long, slender filaments, either parallel or diverging from each other, and often presents the appearance of a lock of cotton whose fibres are electrified so as powerfully to repel each other. These clouds appear to have the least density, the greatest elevation, and the greatest variety of form. They are generally the first to make their appearance after a period of perfectly clear weather. Indeed, in fair weather, the sky is seldom entirely free from small groups of cirrus clouds. They are believed to be composed of spiculæ of ice or flakes of snow floating at a great height in the air. At the height at which they prevail the temperature of the air is below 32° even in midsummer" (Figure 482).

Fig. 482.

"The *cumulus* cloud usually consists of a hemispherical or convex mass, rising from a horizontal base. It is much denser than the cirrus, and is formed in the lower regions of the atmosphere. In fair weather the cumulus often forms a few hours after sunrise, goes on increasing until the hottest part of the day, and disappears about sunset. We often see near the horizon large masses of cumulus clouds, which resemble lofty mountains covered with snow.

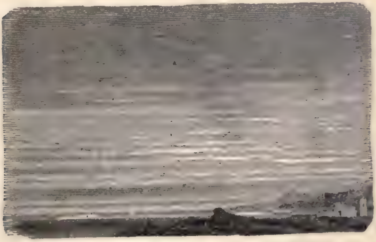
"The rounded top of the cumulus results from the mode of its formation. When the surface of the earth is heated by the rays of the sun, currents of warm air ascend, and as soon as they reach a certain height a portion of their vapor

Fig. 483.

is condensed and forms cloud; and since the upward motion is greatest under the centre of the cloud, the vapor is there carried up to the greatest height" (Figure 483).

The *stratus* cloud is a widely extended horizontal sheet,

Fig. 484.

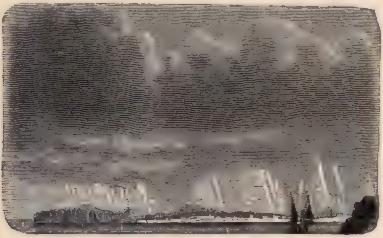


often covering the sky with a nearly uniform veil. It is the lowest of the clouds, and sometimes descends to the surface of the earth (Figure 484).

The *nimbus* is the well-known rain-cloud, consisting of

a combination of cirrus, cumulus, and stratus clouds (Figure 485).

Fig. 485.



560. *The Height and Thickness of Clouds.* — The height of clouds is very variable. The stratus cloud sometimes descends to the surface of the earth. In pleasant weather the under surface of the cumulus cloud is from 3000 to 5000 feet high. Cirrus clouds are never seen below the summit of Mont Blanc.

Clouds are not usually more than half a mile thick, though cumulus clouds sometimes attain a thickness of 3 or 4 miles.

561. *How Clouds are sustained in the Atmosphere.* — Since clouds are composed of particles heavier than air, they must be slowly sinking. They do not ultimately fall to the earth in pleasant weather, because, as they sink, they encounter warmer layers of air which are not saturated with vapor. The cloud is therefore dissipated at the bottom as fast as it falls, while it is at the same time renewed at the top by the condensation of vapor carried up by ascending currents.

562. *Origin of Rain.* — Rain has the same origin as clouds. When the condensation takes place slowly, clouds only are formed; but when it takes place with sufficient rapidity, rain is also formed. To produce an abundant

rain, the air must be suddenly cooled below the dew-point. The most effective way to accomplish this is to force the air up a mile or two above the surface of the earth. Were a mass of air raised two miles from the surface of the earth, its temperature would fall about 35°. The reduction of temperature would be due partially to the chilling effects of expansion and partially to the coldness of the space into which the air would be transported. Were the air of the surface of the earth forced up to this height, most of its vapor would be condensed. The air may be forced upward by the interposition of a mountain range in the path of a current of air, or by the meeting of two opposing currents. Hence mountain ranges are very efficient condensers of the atmospheric vapor. The heaviest rainfall on the globe occurs where the prevailing wind is from the ocean, and where this wind is obliged to pass over a high mountain range on its way to the interior of the continent. On the sheltered side of such mountain ranges there are usually desert regions.

563. *The Amount of Rain in Different Latitudes.* — The average rainfall is greatest at the equator, and decreases as we proceed towards the poles. The annual rainfall at the equator is 104 inches; in latitude 20°, 70 inches; in latitude 30°, 40 inches; and in latitude 60°, 20 inches.

The amount of vapor present in the atmosphere decreases from the equator to the poles, there being about five times as much vapor present in the atmosphere at the equator as in latitude 60°. If the causes which produce rain acted with equal intensity in all latitudes, we should expect that the average rainfall in each latitude would be proportioned to the amount of vapor present in the atmosphere. This, on the basis of 104 inches at the equator, would give 90 inches for the latitude of 20°, 70 inches for the latitude of 30°, and 18 inches for the latitude of 60°. The actual rainfall in latitude 60° is somewhat higher than

the theoretical amount; while in latitudes of 20° and 30° it is considerably less. We must therefore conclude that the causes which tend to produce rain act with less intensity near latitude 30° than they do in the neighborhood of the equator or of latitude 60°. In both of these regions there is an ascent of vast columns of air, due in part to the meeting of opposing systems of winds, the trade-winds in the one case and the middle-latitude and polar currents in the other. The excessive condensation in these regions is one cause of the low barometer which prevails there.

Fig. 486.

564. *Origin of Snow.* — Snow bears the same relation to rain that hoar-frost does to dew. When the vapor of the atmosphere is precipitated at a very low temperature, it at once assumes the solid state, usually in the form of minute crystals. These minute crystals attach themselves to each

other and form snow-flakes, which fall slowly to the earth. Snow-flakes present a great variety of forms, some of which are shown in Figure 486.

When the lower layers of the atmosphere are much above 32°, the snow-flakes melt before they reach the ground, so that rain may fall upon an open plain and snow upon a neighboring mountain, both from the same cloud.

565. *Hail.* — Large hail seldom if ever falls except during thunder-storms. It very rarely follows rain which has continued for some time. The hail covers a much smaller area than the rain-storm, and usually continues at the same place for only five or ten minutes.

Hailstones are of all sizes, from that of small shot up to that of a turkey's egg, and of every variety of shape. One of very irregular form is shown in Figure 487. The centre of large hailstones usually consists of hardened snow, and this is surrounded by a layer of transparent ice. Sometimes we find several alternate layers of opaque snow and transparent ice. Figure 488 shows the section of a hail-stone whose external form is given in Figure 489.

Fig. 487.

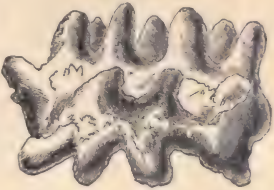


Fig. 488.

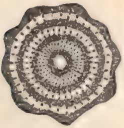
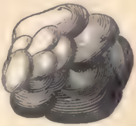


Fig. 489.



566. *Origin of Hail.* — "The formation of hail is invariably attended by two distinct currents of air, and one of these currents displaces the other with great violence. The current of air which precedes the approach of a hail-storm is extremely hot, and highly charged with moisture; and that

which succeeds the fall of hail has an icy chillness. The warm and humid air is displaced by the cold current, and is thus forced up to a great elevation above the earth, by which means its vapor is suddenly condensed. Upon the front of the hail-cloud this condensed vapor exists in the form of water, whose temperature is near 32°. In the interior of the hail-cloud the vapor is precipitated in the form of snow, whose temperature is sometimes as low as 20°.

"Observations on the summits of mountains have shown that on the front of the hail-cloud there exists a violent whirling motion about a horizontal axis. This whirling motion causes the snow to collect in small balls, each of which forms the nucleus of a hailstone. The snow-ball is forced into the warm current, where it receives a layer of water, which is congealed by the nucleus, thus rendering the snowy centre more compact, and adding a shell of transparent ice. By means of the whirling motion, the hailstone, covered with a stratum of uncongealed water, is hurled into the snow-cloud, where it receives a layer of snow, and again becomes thoroughly chilled. Thence it escapes again into the water-cloud, and is covered with a layer of water, which is congealed by the cold of the nucleus. Thus, by the whirling motion, it is plunged alternately into the snow-cloud and the water-cloud, while each alternation furnishes a layer of spongy ice and a layer of transparent ice. Thus the stone grows with immense rapidity, and in a few minutes becomes a large ball three or four inches in diameter.

"The hailstones are sustained in the air by the violent upward motion caused by the cold current displacing the warm one. A sphere of ice two inches in diameter, by falling through a tranquil atmosphere, soon acquires a velocity of 90 feet per second. A hailstone of irregular shape would experience more resistance than a sphere, and

would acquire a somewhat less velocity, but it would still fall from a height of 18,000 feet in about three minutes, which time is too small to allow the formation of masses of ice weighing one pound. An upward current of air, rising with a velocity of 90 feet per second, would sustain a sphere of ice two inches in diameter, and would greatly reduce the velocity of stones of larger size."

D. Storms.

567. *Origin of Storms.* — Any violent and extensive commotion of the atmosphere is called a storm. Such commotions are usually attended by a fall of rain, snow, or hail, but the storm often extends beyond the area of snow or rain, and even beyond the area of clouds.

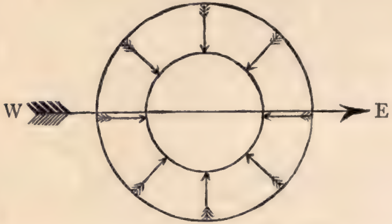
Storms are caused by a strong and extensive upward motion of the air. Since the air is heated by contact with the earth, and by absorption of solar and terrestrial radiations by the watery vapor in it, the atmosphere is heated chiefly at the bottom, the watery vapor existing chiefly in the lower layers. An excessive heating of a mass of air at the surface of the earth, either by contact with a hot surface or by an unusually large absorption, due to an excess of moisture, gives rise to a system of currents such as has been already described. A vertical section of this system of currents is shown in Figure 490; a horizontal section at the bottom, in Figure 491; and a horizontal section at the top, in Figure 492.

Fig. 490.

As the air in the centre of the area rises, it is cooled by expansion at the rate of about 38° for every two miles of ascent. The height to which the air will have to rise to be cooled to its dew-point depends upon the difference between the dew-point and the temperature of the air. As

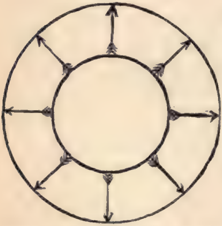
soon as the cloud begins to form, the latent heat of the vapor is liberated. A rainfall of one inch precipitates

Fig. 491.



over two million cubic feet of water upon one square mile of surface, and liberates as much heat over the square mile as it would take to evaporate two million cubic feet of water. It takes over 60,000 units of heat to evaporate one cubic foot of water. The heat thus liberated warms the air in the region in which the condensation takes place, and causes the mass of air to rise still higher. As the air rises higher, more of its vapor is condensed and more heat is liberated.

Fig. 492.



The expansion of the column of air ascending in the centre of a storm, especially after heat begins to be liberated by the condensation, causes the air to spread out in all directions above, making a barometer under the centre of the cloud fall below its mean height, and one beyond the limits of the cloud rise above its mean height. Near the limits of the cloud the air, being heavier, sinks downward, and a portion of it flows along the surface towards the centre of the ascending column, while another portion

flows along the surface in the opposite direction, producing a gentle breeze away from the cloud. The air spreads out more rapidly above than it runs in below, and the storm tends to increase in diameter. Storms often extend with great rapidity till they cover an area of more than a thousand miles in diameter.

When a storm arises some distance to the north of the equator, the surface currents which set in towards its centre are deflected to the right, and so the wind blows in spirally towards the centre. This circulation of the wind around the centre of the storm gives rise to a centrifugal force which tends to whirl the air out from the centre above and to increase the fall of the barometer. The fall of the barometer in the centre of a storm is largely due to the circulation of the air around a rain-area; but the chief agent in originating the disturbance is the rainfall itself. As soon as the rain ceases, the force of the wind declines, and the barometer recovers its mean height.

568. *The Development and Motion of Storms.* — Storms begin gradually, and are usually a day or two in attaining their greatest violence. After a day or two longer their violence again decreases, and at length they disappear or are merged into other storms. A storm occasionally holds out one or two weeks, but it usually lasts only a few days. A storm sometimes remains nearly stationary for a day or two, but it usually moves eastward about 600 miles a day; and though the same storm may continue in existence one or two weeks, it seldom lasts more than one or two days at the same place.

The average direction of storms across the United States is a little north of east, being almost exactly east during the summer. Storms occasionally deviate greatly from their usual track, sometimes moving towards the northeast, sometimes towards the southeast, and occasionally due north.

The average velocity of storms is twenty-six miles an hour, being twenty-one in the summer and thirty in the winter. They occasionally move at the rate of fifty miles an hour, and sometimes remain almost stationary for a day or two.

The direction in which a storm moves is entirely distinct from that of the wind which accompanies it. While the storm moves steadily eastward, the wind has every possible direction at places within the limits of the storm. At places on the north side of the centre of the storm the wind usually sets in from the northeast as the storm approaches, and veers round by the north to the northwest as the storm passes over. At places on the south side of the centre the wind generally sets in from the southeast, and then veers round by the south to the southwest.

Near the centre of a great storm there is usually a lull in the wind, and sometimes a calm. There is seldom any rain, and the clouds often break, and occasionally there is a clear sky for several hours. Soon after the centre of the storm has passed the wind changes to the west, and there is a heavy fall of rain or snow of comparatively short duration.

The winds on the east side of a storm are propagated in a direction opposite to that in which they blow. That is to say, they are propagated *eastward* while they blow westward. Winds propagated, like these, in the opposite direction to that in which they blow are said to be propagated by *aspiration*. The winds on the west of the storm are propagated in the same direction as that in which they blow. Such winds are said to be propagated by *impulsion*.

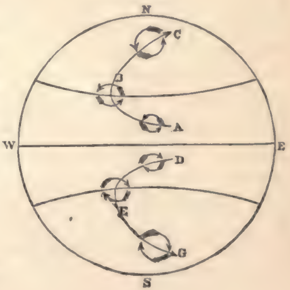
569. *Motion of the Air within Areas of Low and High Barometer.* — "It is found that within the limits of the United States, around every storm-centre, the wind moves spirally inward, circulating about the centre in a direction

contrary to the motion of the hands of a watch, and the average inclination of the winds to a radius drawn from the centre of the storm is almost exactly 45°.

"On the contrary, within an area of high barometer the winds blow *outward*, and the average inclination of the winds to a radius drawn from the centre of the area is also about 45°, but the winds circulate about the centre of the area in the *same* direction as that of the hands of a watch. The former motion, being in the same direction as that observed in violent cyclones, is called *cyclonic;* and the latter motion, being in the opposite direction, is called *anti-cyclonic.*"

570. *Cyclones.* — "The inequalities of the earth's surface, especially in hilly countries, greatly modify the direction of the wind, so that in great storms the movements of the atmosphere often seem very complex and anomalous. Over the ocean these disturbing causes do not exist, and here we find that in violent storms the movements of the air are much more regular and uniform. This motion of the wind has generally been found to be in great circuits, spirally inward toward the centre of the storm, and such storms are now commonly designated by the term *cyclone.* These storms prevail in the neighborhood of the West India Islands, where they have long been known by the name of *hurricanes.* They are also common in the China Sea and in the Indian Ocean, on both sides of the equator."

Fig. 493.



Cyclones originate near the equatorial lim-

its of the trade-winds on either side of the equator, and move northward and southward in parabolic paths, as shown in Figure 493. The small arrows indicate the direction of the circulation of the wind in the cyclone itself. *Tornadoes* are only very violent storms, caused by a sudden and very great fall of pressure.

571. *Predictions founded upon the Established Laws of Storms.* — "The laws of storms are now so well understood that we can predict with some confidence the changes which will succeed at any place during the next few hours, provided we can know the state of the weather throughout the surrounding region to a great distance. This is what has been attempted since 1871 by the United States Signal Service, and the general accuracy of these predictions has excited considerable surprise. Such predictions would be still more reliable if we could have information respecting the various meteorological elements from a larger portion of the earth's surface. The centre of a large portion of our storms follows nearly the northern boundary of the United States, so that our observations inform us respecting only one half, or perhaps less than one half, of the storm-area. Moreover, storms are often affected by changes which are going on in very distant quarters. An area of unusually high barometer may affect the course of a storm whose centre is distant two or three thousand miles; and an unusual fall of rain in the equatorial regions may cause an unusual overflow of air to the middle latitudes, resulting in serious disturbances of atmospheric pressure. When the laws of storms have been more precisely defined, and telegraphic reports can be received from a more extended area, we shall doubtless be able to predict coming storms with greater precision."

VI.

ELECTRICAL PHENOMENA OF THE ATMOSPHERE.

A. Atmospheric Electricity.

572. *Electrical Condition of the Atmosphere.*—The atmosphere is almost always charged with electricity, and usually with positive electricity. There are, however, great variations in the intensity of the charge, and clouds are frequently charged with negative electricity.

The intensity of atmospheric electricity varies regularly with the hour of the day and with the season of the year. During the day it is least intense at 4 A.M. and at 4 P.M., and most intense at 10 A.M. and at 10 P.M. It is least intense during the summer months and most intense during the winter months. The intensity of atmospheric electricity also increases with the altitude above the surface of the earth.

When the sky is covered with clouds there are frequent changes in kind as well as in intensity of atmospheric electricity, the atmospheric being sometimes positive and sometimes negative. It is seldom negative, however, except when rain is falling. When snow is falling, the lower layer of air becomes highly charged with electricity. During a thunder-shower the electricity of the air frequently changes in two or three minutes from positive to negative, and back to positive again, and sometimes half a dozen of these changes occur during a single shower.

573. *Origin of Atmospheric Electricity.* — The following account of the origin of atmospheric electricity is taken from Loomis: "Evaporation is probably the principal source of atmospheric electricity. The following experiment shows the production of electricity by evaporation. If upon the top of a

gold-leaf electrometer we place a metallic vessel containing salt water, and drop into the water a heated pebble, the leaves of the electrometer will diverge. The vapor which rises from the water is charged with positive electricity, while the water retains negative electricity.

"The water used in this experiment must not be perfectly pure, but must contain a little salt, or some foreign matter. The evaporation of the water of the ocean must therefore furnish a large amount of electricity, and fresh water must also furnish some electricity, for the water of the earth is never entirely pure.

"The diurnal variation in the intensity of atmospheric electricity is to be ascribed partly to real changes in the amount of electricity present in the air, and partly to variations in the conducting power of the air.

"Just before sunrise the electricity has a feeble intensity, because the moisture of the preceding night has transmitted to the earth a portion of the electricity which was previously present in the air. After the sun rises, new vapor ascends and carries with it positive electricity, so that the amount of electricity in the air increases. Toward noon the air becomes dry, and transmits less readily the electricity accumulated in the upper regions of the atmosphere; so that, although the amount of electricity in the air is continually increasing, an electrometer near the earth's surface indicates an apparent diminution.

"Toward evening the air grows cool, again becomes humid, and transmits more readily to the earth the electricity accumulated in the upper regions of the atmosphere. The effect produced upon an electrometer therefore increases until some hours after sunset; but since during the night there is a constant discharge of electricity from the air to the earth the electrometer soon indicates a diminished intensity, which continues until towards morning.

"The same principle explains why the electricity of the air appears less intense in summer than in winter. In summer the air is warm and dry, and opposes more resistance to the flow of electricity from the higher regions of the atmosphere, while in winter the moist air produces a contrary effect; so that, although the atmosphere doubtless contains more electricity in summer

than in winter, it generally produces a less effect upon an electrometer placed near the earth's surface.

"We have found that the atmosphere ordinarily contains a large quantity of electricity. Since dry air is a non-conductor, the electrified particles in clear weather are in a measure insulated, and the electricity cannot acquire much intensity; but when the vapor of the air is precipitated and a cloud is formed, the electricity which was previously confined to the separate particles of the air now finds a conducting medium more or less perfect, and it spreads itself over the surface of the cloud, thereby acquiring considerable intensity. It is generally admitted that the same quantity of electricity which exists in the cloud existed in the air before the formation of the cloud, and that the cloud performs no other office than that of a conductor.

"A cloud thus electrified must necessarily have positive electricity, since in clear weather the electricity of the atmosphere is always positive. Such a cloud, when it approaches near another cloud having less electricity, or none at all, acts by induction upon the latter, decomposing its natural electricity, attracting the negative electricity and repelling the positive. The positive electricity thus repelled may be sometimes drawn off by near approach to another cloud, or to the earth, leaving only negative electricity upon the cloud. Hence probably result the frequent alternations of positive and negative electricity observed during a thunder-shower."

B. Lightning.

574. *Lightning.* — "Two clouds having opposite electricities attract each other, and when the clouds come sufficiently near, the two electricities rush towards each other with great violence. This phenomenon is called *lightning*, and is accompanied by an explosive noise called *thunder*.

"Since clouds are very imperfect conductors, when the electricity of one part of a cloud is discharged, the electricity of a distant part of the cloud is but slightly changed. Thus, a single discharge does not establish a complete electrical equilibrium; but there is a change in the distri-

bution of the electricities upon the surrounding clouds, and there must be a succession of discharges before the electricity is entirely neutralized. Hence results a succession of flashes of lightning and peals of thunder.

"A cloud charged with electricity exerts an inductive influence upon the earth's surface immediately beneath it, decomposing its natural electricities, repelling electricity of the same kind, and attracting the opposite kind. Accordingly there will sometimes be a discharge of electricity from the cloud to the earth. This charge is usually received by the most elevated objects, such as mountains, hills, trees, spires, high buildings, etc. Trees are particularly exposed to strokes of lightning on account of their elevation, as well as of the moisture which they contain, and which renders them partial conductors of electricity."

575. *Lightning-Rods.* — Buildings may be protected from injury by the use of *lightning-rods*. These are metallic rods running from the top of the building to the ground. The rods must not be too small, and their parts must be well connected so as to be in good metallic contact. They should run well into the earth at the bottom, and be carefully pointed at the top. There ought to be several sets of points on the top of the building connected by metallic rods with each other and with the rod that runs to the ground; and if the building is at all large there ought to be several rods running to the ground, all connected together by metallic rods. If the building has a metallic roof, or there are metallic pipes or other masses of metal in the interior, these should all be carefully connected with the rod. The points are designed to facilitate the escape of the electricity from the building and the ground around it when these are acted upon inductively by the cloud, so as to prevent electricity from accumulating upon them. This accumulation of electricity upon an object always precedes a violent discharge between it and the cloud;

and if the accumulation can be prevented no violent discharge will take place. Should the electricity be developed by induction more rapidly than it can escape silently from the points, and a spark discharge should take place, the rod serves as the path of least resistance, and the discharge will take this path rather than pass through the building, which offers greater resistance.

576. *Forms of Lightning.* — "Lightning exhibits a variety of forms, which have been designated by the terms *zigzag*, *ball*, *sheet*, and *heat lightning*.

"*Zigzag lightning* presents a long, irregular, jagged line of light, like the ordinary spark drawn from an electric machine. This zigzag path is sometimes four or five miles, and perhaps even ten miles in length."

"*Ball lightning* appears like a ball of fire, and is usually accompanied by a terrific explosion. It probably results from a charge of electricity unusually intense, which forces a direct instead of a circuitous passage through the air.

"Some have supposed that ball lightning was the agglomeration of ponderable substances in a state of great tenuity, strongly charged with electricity."

"*Sheet lightning* is a diffuse glare of light, sometimes illuminating only the edges of a cloud, and sometimes spreading over its entire surface.

"This may be sometimes due to distant lightning which illumines a cloud, while the direct flash is hidden from the observer by intervening clouds. Sometimes it may result from a movement of electricity in the interior of a cloud which is a very imperfect conductor, producing an illumination analogous to that observed on a plate of moist glass employed in discharging an electrical machine.

"During the evenings of summer the horizon is sometimes illumined for hours in succession by flashes of light unattended by thunder. This is called *heat lightning*. This illumination is sometimes due to the reflection from

the atmosphere of the lightning of clouds so distant that the thunder cannot be heard.

"Sometimes, however, this light overspreads the entire heavens, showing that the electricity of the clouds escapes in flashes so feeble that they produce no audible sound. Such cases may occur when the air is very moist, the air being then a tolerable conductor, and offering just sufficient resistance to the passage of the electricity to develop a feeble light."

577. *Thunder.* — The light of lightning proceeds from the air, which is heated white-hot along the line of discharge by the passage of the electricity. The thunder seems to be the noise produced by the sudden expansion and contraction of this heated line of air.

Sound travels only 1100 feet a second, while the transmission of light is nearly instantaneous. Hence the sound does not reach the ear until some time after the flash is seen. By observing the interval between the flash and the report, the distance of the point of discharge can be ascertained, sound travelling a mile in about five seconds. Thunder is seldom heard more than ten miles away.

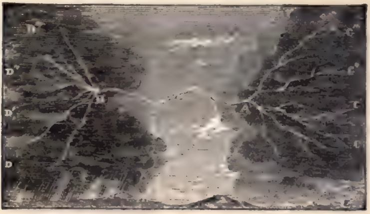
The sound is produced instantaneously at every point along the line of the flash, but, since different parts of the flash are usually at unequal distances from the observer, the sound from different points will reach the ear in slow succession, producing a prolonged peal of thunder. The prolonged duration of some peals of thunder is in part due to echoes, produced by reflection from the sides of mountains or from clouds.

The variable intensity or *rolling* of thunder is due partly to the zigzag course of the discharge, which often brings several points of the flash equally distant from the observer (the sounds from these points reach the ear simultaneously, and so produce a sound of double and triple the intensity); and partly to the unequal distance of different

parts of the flash, the sound decreasing in intensity as the square of the distance increases. The rolling of thunder is in part also the effect of echoes.

Thunder often begins with a rattling sound, followed by a loud peal of variable intensity, and ends with a low rattling sound. This succession of sounds may be due to a discharge like that represented in Figure 494. An observer at E would first hear a rattling sound from the branches $A\ C$, $A\ C'$, etc., from the first cloud, and then a loud

Fig. 494.



crash of variable intensity from the concentrated discharge between A and B, and finally a rumbling sound from the branches $B\ D$, $B\ D'$, etc., of the distant cloud, the noise being feeble on account of the great distance.

C. The Aurora.

578. *The Polar Light.* — The polar light is a luminous appearance frequently seen near the horizon as a diffused light, similar to that of the dawn, whence it has received the name of *aurora.*

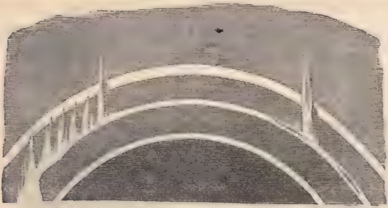
579. *Varieties.* — "Auroras exhibit an infinite variety of appearances, but they may be generally referred to one of the following classes: —

"*First. A horizontal light like the morning aurora or break of day.* The polar light may generally be distin-

guished from the true dawn by its position in the heavens, since in the United States it always appears in the northern quarter.

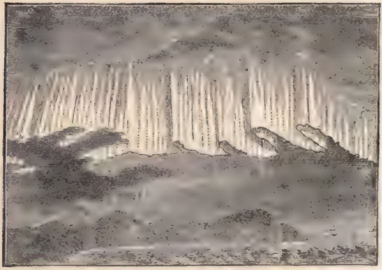
"*Second. An arch of light somewhat in the form of a rainbow.* This arch frequently extends entirely across

Fig. 495.



the heavens from east to west, and cuts the magnetic meridian nearly at right angles. This arch does not long remain stationary, but frequently rises and falls; and when

Fig. 496.



the aurora exhibits great splendor several parallel arches are often seen at the same time, appearing as broad belts of light, stretching from the eastern to the western horizon (Figure 495).

"The auroral arches exhibit great varieties of form, sometimes presenting the appearance of a brilliant curtain, whose folds are agitated by the wind (Figure 496.)

"*Third. Slender, luminous beams or columns*, well defined, and often of a bright light. These beams rise to various heights in the heavens, from 20° or 30° up to 90° or more, sometimes, though rarely, passing the zenith. Their breadth varies from a quarter of a degree up to two or three degrees. Frequently they last but a few minutes, sometimes they continue a quarter of an hour, a half-hour, or even a whole hour. Sometimes they remain at rest, and sometimes they have a quick lateral motion. This light is commonly of a pale yellow, sometimes reddish, occasionally crimson, or even of blood color. Sometimes the luminous beams are interspersed with dark rays resembling dense smoke. Sometimes the tops of the beams are pointed, and, having a waving motion, they resemble the lambent flames of half-extinguished alcohol burning upon a broad flat surface.

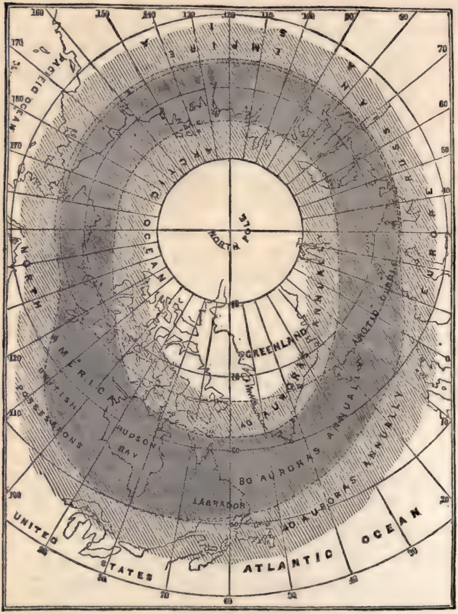
"*Fourth.* Luminous beams sometimes shoot up simultaneously from nearly every part of the horizon, and converge to a point a little south of the zenith, forming a quivering canopy of flame, which is called the *corona*. The sky now resembles a fiery dome, and the crown appears to rest upon variegated fiery pillars which are frequently traversed by waves or flashes of light. This may be called a *complete aurora*, and comprehends most of the peculiarities of the other varieties.

"*Fifth. Waves or flashes of light.* The luminous beams sometimes appear to shake with a tremulous motion, flashes like waves of light roll up toward the zenith, and sometimes travel along the line of an auroral arch. Sometimes the beams have a slow lateral motion from east to west, and sometimes from west to east. These sudden flashes of auroral light are known by the name of *merry*

dancers, and form an important feature of nearly every splendid aurora."

580. *Height and Distribution of Auroras.* — From a large number of observations, it is concluded that the aurora seldom appears at a less elevation than 45 miles from the earth's sur-

Fig. 497.



face, and that it frequently extends upward to an elevation of 500 miles. Auroras occur most frequently in the higher latitudes, and are seldom seen within the tropics. In North America they are most frequent between latitudes 50° and 60°. In

this belt they are seen almost every night, and they appear high in the heavens. Farther north they are less frequent, and are seldom seen except towards the south. The belt of greater auroral activity in the northern hemisphere is shown in Figure 497. It is farther north in Europe than in America. It bears considerable resemblance in form to a magnetic parallel.

Auroras are as numerous in the southern hemisphere as in the northern, and probably have a corresponding geographical distribution. Probably all great auroral displays take place simultaneously in both hemispheres.

581. *Periodicity of Auroras.* — There is a *diurnal*, an *annual*, and a *secular* periodicity in auroral displays. The maximum frequency and brilliancy of auroras during the day occurs about midnight, and during the year from April to September. The annual maximum is less evident, because of the shorter evenings, but careful observation shows that there is a decided diminution in the frequency of auroras during the winter. The grandest displays of the aurora occur at intervals of about 60 years, while a less marked periodic fluctuation occurs every 10 years. These two periods of secular variation in the aurora correspond in a remarkable manner with those of the daily fluctuation of the magnetic needle and those of sun-spot frequency.

582 *Theory of the Polar Light.* — The following account of the theory of the aurora is abridged from Loomis, with slight changes of expression : —

Auroral exhibitions take place in the upper regions of the atmosphere and partake of the earth's rotation. All the celestial bodies have an apparent motion from east to west, arising from the rotation of the earth ; but bodies belonging to the earth, including the atmosphere and the clouds which float in it, partake of this rotation, so that their relative position is not affected by it. The same is true of the aurora. Whenever a corona is formed, it maintains sensibly the same position in the heavens during the whole period of its continuance, although the stars meanwhile revolve at the rate of 15° per hour.

The colors of the aurora are the same as those of ordinary electricity passed through rarefied air. When a spark is drawn from an ordinary electrical machine in air of the usual density,

the light is intense and nearly white. If the electricity is passed through a glass vessel in which the air has been partially rarefied, the light is more diffuse and inclines to a delicate rosy hue. If the air is still further rarefied, the light becomes very diffuse, and its color becomes a deep rose or purple. The same variety of colors is observed during the aurora. The transition from a white or pale straw color to a rosy hue, and finally to a deep red, probably depends upon the height above the earth, and upon the amount of condensed vapor present in the air.

The formation of an auroral corona near the magnetic zenith is the effect of perspective, resulting from a great number of luminous beams all parallel to each other. A collection of beams parallel to the direction of the dipping needle would appear to converge towards the pole of the needle, and no other supposition will explain all the appearances which we observe. The auroral crown, therefore, everywhere appears in the magnetic zenith, and it is not the same crown which is seen at different places any more than it is the same rainbow which is seen by different observers.

The auroral beams are simply illumined spaces caused by the flow of electricity through the upper regions of the atmosphere.

The slaty appearance of the sky which is remarked in all great auroral exhibitions arises from the condensation of the vapor of the air, and this condensed vapor probably exists in the form of minute spiculæ of ice or flakes of snow. Fine flakes of snow have been repeatedly observed to fall during the exhibition of auroras, and this snow only slightly impairs the transparency of the atmosphere, without presenting the appearance of clouds. It produces a turbid appearance of the sky, and causes that dark bank which in the United States rests on the northern horizon. This turbidness is more noticeable near the horizon than it is at great elevations, because near the horizon the line of vision traverses a greater depth of this hazy atmosphere. When the aurora covers the whole heavens, the entire atmosphere is filled with this haze, and a dark segment may be observed resting on the southern horizon.

The vapor which arises from the ocean in all latitudes, but most abundantly in the equatorial regions of the earth, carries into the upper regions of the atmosphere a considerable quantity

of positive electricity, while the negative electricity remains in the earth. This positive electricity, after rising nearly vertically with the ascending currents of the atmosphere, would be conveyed towards either pole by the upper currents of the atmosphere.

The earth and the rarefied air of the upper atmosphere may be regarded as forming the two conducting plates of a condenser, which are separated by an insulating stratum, namely, the lower portion of the atmosphere. The two opposite electricities must then be condensed by their mutual influence, especially in the polar regions, where they approach nearest together, and whenever their tension reaches a certain limit there will be discharges from one conductor to the other. When the air is humid it becomes a partial conductor, and conveys a portion of the electricity of the atmosphere to the earth. On account of the low conducting power of the air, the neutralization of the opposite electricities would not be effected instantaneously, but by successive discharges, more or less continuous and variable in intensity. These discharges should frequently occur simultaneously at the two poles, since the electric tension of the earth should be nearly the same at each pole.

Fig. 498.

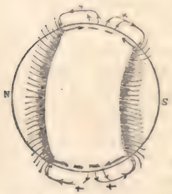


Figure 498 represents the system of circulation here supposed, the north and south poles of the earth being denoted by the letters *N* and *S*.

When electricity from the upper regions of the atmosphere discharges itself to the earth through an imperfectly conducting medium, the flow cannot be everywhere uniform, but must take place chiefly along certain lines where the resistance is least; and this current must develop light, forming thus an auroral beam. It might be expected that these beams would have a vertical position, but their position is controlled by the earth's magnetism. It is found that when magnetic forces act upon a perfectly flexible conductor through which an electric current passes, the conductor must assume the form of a magnetic curve. Now at each point of the earth's surface the dipping needle shows the direction of the magnetic curve which passes through its

base; and since adjacent streamers are sensibly parallel, the beams appear to converge towards the magnetic zenith.

When electricity escapes from a metallic conductor under a receiver from which the air has been exhausted, and this conductor is the pole of a powerful magnet, the electric light forms a complete luminous ring around it.

In like manner, the auroral arch is a part of a luminous ring nearly parallel to the earth's surface, having the magnetic pole for its centre, and cutting all the magnetic meridians at right angles; and this position results from the influence of the earth's magnetism.

The flashes of light observed in great auroral displays are due to *inequalities* in the motion of the electric currents. On account of the imperfect conducting power of the air the flow of electricity is not perfectly uniform, but escapes by paroxysms. The flashes of the aurora are therefore feeble flashes of lightning.

The three phenomena — solar spots, mean daily range of the magnetic needle, and frequency of auroras — exhibit two distinct periods: one a period of from ten to twelve years, the other a period of from fifty-eight to sixty years. The first of these periods corresponds to one revolution of Jupiter, and the second to five revolutions of Jupiter or two of Saturn; and we can scarcely doubt that the phenomena depend upon the movements of these planets. Observations have also indicated subordinate fluctuations, which are probably due to the action of Venus.

We do not know how the planets exert an influence upon the sun's surface, but we may suppose that there are circulating round the sun powerful electric currents, which may possibly be the source of the sun's light; these currents may act upon the planets, developing in them electric currents, and the currents circulating round the planets may react upon the solar currents with a force varying with their distances and relative positions, exhibiting periods corresponding to the times of revolution of the planets. These disturbances of the solar currents may be one cause of the solar spots, and an unusual disturbance of the solar currents may cause a disturbance of the currents of the earth's surface, giving rise to unusual displays of the aurora.

The geographical distribution of auroras depends chiefly upon the relative intensity of the earth's magnetism in different latitudes. According to experiments with artificial magnets, the electric light tends to form a ring around the pole, and at some distance from it. The electric light should therefore be most noticeable in the neighborhood of the earth's magnetic pole, but not directly over it. Auroras are, accordingly, most abundant along a certain zone which follows nearly a magnetic parallel, being everywhere nearly at right angles to the magnetic meridian of the place.

The electricity of the tropical regions has great intensity, and moves with explosive violence in thunder-showers, while the magnetic intensity in those regions is very feeble, and is not sufficient to control the movements of the electricity. In the higher latitudes thunder-showers become infrequent, the electricity of the atmosphere passes to the earth in a slow and quiet manner, and these discharges are controlled by the magnetism of the earth.

We cannot explain the great auroral displays in the northern hemisphere by supposing that the electricity of the atmosphere is temporarily diverted from one hemisphere to the other, for the mean range of the magnetic needle exhibits its maxima simultaneously in both hemispheres; neither can we suppose that the absolute amount of electricity for the entire globe, as developed by evaporation from the water of the ocean, undergoes great periodical variations, for the mean temperature of the earth's surface does not change sensibly from one year to another. We seem, therefore, compelled to ascribe these great auroral displays in no small degree to the direct action of the sun, through the agency, perhaps, of its magnetism, or of the electric currents circulating around it. Such an effect should take place simultaneously in both hemispheres.

VII.

OPTICAL PHENOMENA OF THE ATMOSPHERE.

A. Refraction.

583. *Astronomical Refraction.* — When a ray of light from a star or other heavenly body enters the atmosphere obliquely, it will be bent downward, or towards a vertical line drawn from the point of contact of the ray with the atmos-

Fig. 499.

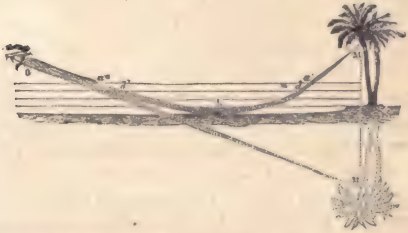
phere to the surface of the earth; and as the atmosphere grows denser as we approach the earth, the ray will be bent more and more as it passes through the atmosphere from layer to layer. As we always see the body which emits the ray in the direction of the ray when it enters the eye, the effect of this refraction will be to make every heavenly body appear farther above the horizon and nearer the zenith than it really is. A star in the zenith is not displaced by refraction, because the rays from it enter

the air perpendicularly, and therefore without bending. The farther a star is from the zenith, the more obliquely its rays enter the atmosphere, and the greater the refraction.

584. *Mirage.* — Objects within the atmosphere are sometimes displaced or made to appear double by the refraction of the air. The change in the appearance of objects within our atmosphere due to atmospheric refraction, is called ***mirage.***

585. *Mirage upon a Desert.* — Upon a hot desert, on a still day, objects are often seen reflected in a lower stratum of air so as to give the appearance of water (Figure 499).

Fig. 500.



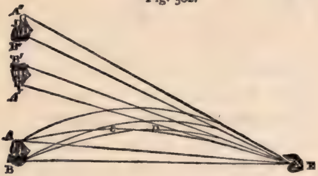
The layers of air near the hot sand become more heated, and consequently rarer, than those higher up. Hence rays coming from any object, as the tree (Figure 500), would, on passing downward, be entering continually rarer and rarer layers of air. They would therefore be bent upward more and more, till they finally meet a layer at an angle exceeding the limiting angle, and become totally reflected. This total reflection of the rays causes objects to be mirrored in the layers of air as in the surface of water.

586. *Mirage over Water.* — Objects at a distance over water, partially or entirely below the horizon, often appear suspended in the air, sometimes erect, sometimes inverted,

and sometimes both erect and inverted, as shown in Figure 501. In this case the layers of air near the cold surface of the water are considerably

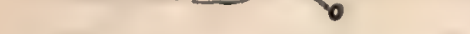
Fig. 501.

Fig. 502.



colder and denser than those higher up. Rays, therefore, which pass upward from an object are continually entering rarer layers of air, and are therefore bent more and more downward, as shown in Figure 502. If the rays $A\,C$ and $B\,D$, coming from the top and bottom of the object, are totally reflected at the points C and D, they will cross on their way to the eye, and cause the object to appear elevated and inverted at $A'B'$. If the rays coming from the top and bottom of the object are simply bent round without being totally reflected, they will not cross before entering the eye, and the object will appear elevated and erect, as at $A''B''$. The elevation of an object by refraction without inversion is sometimes called *looming*. Sometimes objects entirely below the horizon are elevated by refraction sufficiently to appear distinctly above the horizon.

Fig. 503.



587. *Lateral Mirage.*—Sometimes vertical layers of air near a shaded bank will be much colder and denser than layers farther out which are exposed to the sun. This gives rise to a *lateral* mirage, similar to that over the water. An observer at B (Figure 503) would in this case see the vessels C and

D reflected at *C'* and *D'*, as in the surface of a vertical mirror. Sometimes near a hot well there occurs a case of lateral mirage similar to the mirage over a desert.

588. *The Rainbow.* — The rainbow, when complete, is a colored arc having a radius of about 41°, and containing all the prismatic hues, the red being on the outside of the arc and the violet on the inside. There is often a second fainter bow, with its colors in the reverse order, outside of the primary bow. This is called the *secondary* bow. Occasionally, there are one or more *supernumerary* bows within the primary bow, composed of colored arcs of greater or less extent.

The rainbow appears whenever the sun shines upon falling rain in the opposite part of the heavens. The bow is never seen unless the sun is within 41° of the horizon, and the nearer the sun is to the horizon the larger the arc of the bow.

A line drawn from the sun through the eye of the observer points to the centre of the circle of which the rainbow is a part, and is called the *axis* of the bow. A line drawn from the eye of the observer to the centre of the colored band at any point makes an angle of about 41° with the axis of the bow. A line drawn from the eye of the observer to the red edge of the bow makes an angle of about 42½° with this axis; and one drawn to the violet edge, an angle of about 40½°.

When the sun is on the horizon, the centre point of the bow will also be on the horizon opposite the sun, and the middle point of the arc will be 41° above the horizon. When the sun is above the horizon, the centre of the bow will be below the horizon, and the middle point of the arc nearer the horizon. When the sun is 41° above the horizon, the centre of the bow will be 41° below the horizon, and the middle of the arc on the horizon.

589. *Explanation of the Rainbow.* — The rainbow is pro-

duced by rays of sunlight reflected from the rear surface of the rain-drops. These rays would be refracted both on entering and leaving the drops. At each refraction they would be bent towards a line drawn to the point of contact of the ray with the rear surface of the drop, and parallel with the incident ray of sunlight, and therefore parallel with the axis of the bow (Figure 504). If we trace the path of every ray of sunlight through a rain-drop according to Snell's law of refraction, we shall find that at an angle of 41° with the axis of the bow the rays emerge from the rain-drop crowded together and almost *parallel* with each other (Figure 505). These rays are able to preserve their intensity through long atmospheric distances. At all other angles the emergent rays are divergent, and through their divergence they become too feeble to affect the eye. Accordingly, whenever the observer looks 41° away from the axis of the bow, his eye catches some of these nearly parallel rays which are emerging from some rain-drop. He therefore sees a bright band, circular in form, and having a radius of 41°.

Fig. 504.

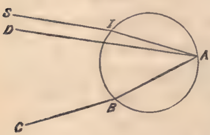
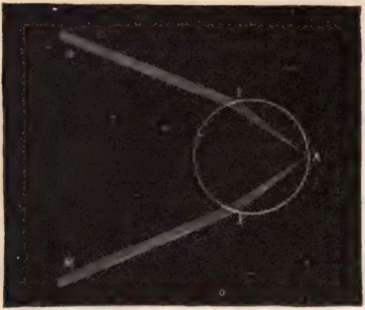


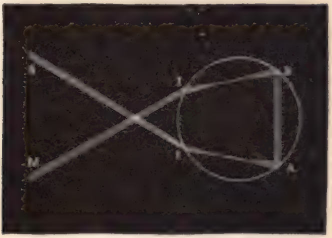
Fig. 505.



The different colored rays are refracted unequally on their

passage through the rain-drop; hence the angle of parallelism is somewhat different for different colors, being about 42½° for the red and about 40½° for the violet. This accounts for the colors of the rainbow, the violet rays reaching the eye from drops nearer the axis than those which send red rays to the eye. No

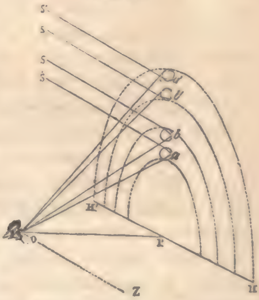
Fig. 506.



two observers see the same rainbow; that is to say, no two eyes receive the colors from the same set of rain-drops.

The *secondary* bow is produced by rays that have suffered two reflections within the rain-drops (Figure 506). Figure 507 shows the relative position of the two bows.

Fig. 507.



The supernumerary bows are due to the interference of rays which emerge from rain-drops in nearly the same direction after having suffered different degrees of retardation, so as to bring their waves into opposite phases. One of these rays suffers more retardation within the rain-drop than another, because it has a longer path within the drops. As a rule, rays of light are retarded in traversing a denser medium.

B. Reflection.

590. *Diffused Daylight.* — When the sun shines upon any portion of the atmosphere, the particles of air reflect the rays of light irregularly, and so scatter the light in every direction, thus giving rise to *diffused* daylight. Were it not for the atmosphere, shadows would be utterly devoid of light, and rooms into which the sun was not directly shining would be totally dark.

591. *Twilight.* — Were it not for the atmosphere, the darkness of midnight would begin the moment the sun sank below the horizon, and would continue till he rose again above the horizon in the east, when the darkness of the night would be suddenly succeeded by the full light of day. The gradual transition from the light of day to the darkness of the night, and from the darkness of the night to the light of day, is called *twilight*, and is due to the diffusion of light from the upper layers of the atmosphere after the sun has ceased to shine on the lower layers at night, or before it has begun to shine upon them in the morning.

Twilight begins and ends when the sun is about 18° below the horizon.

592. *Color of the Sky.* — Large particles reflect and diffuse all luminous waves equally well, but a particle intermediate in size between a red and a violet wave would reflect a greater proportion of violet waves than of red waves. The smaller the particles suspended in a transparent medium, the greater the proportion of blue rays reflected and the less the proportion of red. Hence any transparent medium holding very minute particles of any kind in suspension will appear blue in reflected light. According to Tyndall, the sky owes its blue color to the minute particles of watery vapor or other substance suspended in it. The more minute the particles, the bluer the

sky. As we approach the horizon the sky inclines to white, because of the larger particles which are present in the lower layers of the atmosphere.

When the sun is near the horizon, the rays traverse a greater atmospheric distance, and the separation between the long and short waves is more complete. In this case the rays which reach us, and which illumine the clouds and the lower portion of the sky, are those which are allowed to pass the particles, and not those which are reflected by them. Hence the evening sky inclines to yellow, orange, or red, according as the shorter waves have been more or less completely turned back. Unless there are clouds in the upper portions of the sky, these colors are limited to the regions near the horizon, since it is there only that the particles in the air are large enough to reflect the larger waves transmitted to them.

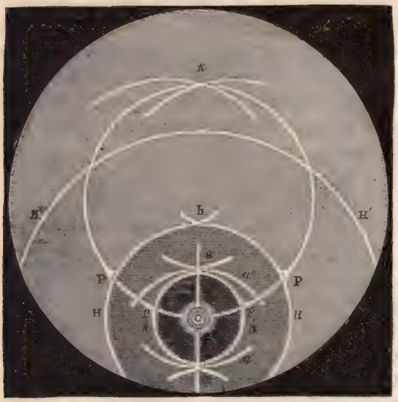
C. Coronæ and Halos.

593. *Coronæ.* — When light fleecy clouds pass over the sun or moon, one or more iris-colored rings are often seen about these bodies, the inner ring being from 3° to 6° in diameter. The blue edges of these rings are towards the sun or moon, and the red edges away from it. These rings are called *coronæ.* They are more frequently noticed about the moon than about the sun, owing to the dazzling brilliancy of the latter. They are caused by the *diffraction* of the rays of light as they pass through the small spaces between the particles of the cloud. They are shown at the centre of the lower part of Figure 508.

594. *Halos.* — Halos are circles formed around the sun or moon. When bright they are seen to be composed of the prismatic colors. They are larger than coronæ, and are red on the edge towards the sun. The halo most often seen has a radius of 22°. This is shown at *h h* (Figure 508). A second halo is sometimes formed having a

radius of 46°, HH; and occasionally a third halo is seen having a radius of about 90°, $H' H'$. These halos are formed by the refraction of the rays of light on their passage through crystals of ice floating in the atmosphere. Even in midsummer, at a moderate elevation above the surface of the earth, the condensed vapor is frozen. These ice crystals may be numerous enough to form circles about the sun and moon without giving the appearance of

Fig. 508.



a cloud. When present they impart a greater or less degree of haziness to the atmosphere. The simplest form of an ice crystal is a right prism, whose section is a regular hexagon, and whose sides are perpendicular to its base. The alternate sides of such a prism are inclined to each other at an angle of 60°.

The halo having a radius of 22° is formed by the refraction of the rays of light which pass through the alternate sides of the prism; and the halo of 46°, by the refraction

of the rays passing through one side and the adjacent base. The halo of 90° appears to be formed by rays which suffer one internal reflection on passing through the crystal.

595. *Parhelic Circle.* — "When a halo is formed around the sun we often notice a white circle passing through the sun and parallel to the horizon (Figure 508). This is called a *parhelic* circle, and is produced by the reflection of the sun's light from ice prisms or snow crystals whose surfaces have a vertical position. When the air is tranquil, the flakes of snow which are present in the atmosphere descend slowly to the earth, and they tend to assume that position in which they experience the least resistance from the air. For most forms of snow-flakes, this position will be when the principal faces of the crystal are perpendicular to the horizon, and the light of the sun may reach the eye reflected from such snow-flakes as are situated on a horizontal circle passing through the sun. This circle never exhibits prismatic colors like the first-mentioned halos."

596. *Parhelia.* — "Near those points where halos cut the parhelic circle there is a double cause of light, and here the illumination is sometimes so great as to present the appearance of a mock sun, *p p* and *P P* (Figure 508), and is called a *parhelion.*

"Parhelia are generally red on the side which is toward the sun, and they sometimes have a prolongation in the form of a tail several degrees in length, whose direction coincides with that of the horizontal circle."

597. *Contact Arches.* — "Arcs of colored circles with variable curvatures are sometimes seen touching the halos of 22° and 46° at their highest and lowest points, *a*, *b* (Figure 508). These are due to the refraction of the sun's light through ice prisms, some of them having their axes perpendicular to the sun's rays, and others inclined at various angles, but all in a horizontal position. The sun's light, refracted by such prisms as have their axes not only

horizontal, but perpendicular to the solar rays, will produce a bright image directly over or under the sun. But the sun's light, passing through prisms whose axes are inclined to the solar rays, will experience a greater deviation, and also a deflection from a vertical plane. Thus, if we look at a long straight bar through a prism whose axis is parallel to the bar, the straight bar appears curved, the deviation being greatest in the case of those rays which are oblique to the axis of the prism."

"Sometimes we notice two arcs of circles nearly white, *A* (Figure 508), intersecting the parhelic circle at a point directly opposite to the sun, and inclined to this circle at angles of about 60°.

"They are probably due to reflection from surfaces oblique to the horizon."

598. *Vertical Columns passing through the Sun.* — "Sometimes, near sunset, we notice a luminous column, perpendicular to the horizon, rising from the sun to a height of 10° or 15°, and occasionally still higher. This column is due to the reflection of the sun's light from the under faces of ice crystals, which are nearly parallel to the horizon. Sometimes, a little before sunset, a similar column of light is seen to shoot down from the sun toward the horizon. This is formed in a similar manner by rays of the sun reflected from the upper faces of crystals in a nearly horizontal position. Sometimes columns are seen simultaneously both above and below the sun; and if the halo of 22° is seen at the same time, this column, together with the parhelic circle, presents the appearance of a rectangular cross within the halo (Figure 508). These luminous columns are probably formed only when the air is very tranquil, and the reflecting surfaces may be the rectangular terminations of spiculæ of ice, which are slowly falling to the earth with their axes nearly in a vertical position.

"When we remember the immense variety in the forms

of snow-flakes, a few of which are represented in Figure 486, we should anticipate a very great variety in the figures which might be produced from the refraction or reflection by them of the sun's light."

VIII.

THE THREE GREAT CIRCULATIONS OF THE GLOBE.

599. *The Atmospheric Circulation.* — In the atmospheric circulation, which gives rise to the various systems of winds, masses of air are kept moving round and round. This circulation is maintained by heat received from the sun, and absorbed by the atmosphere. The heat thus absorbed causes the air to expand, rise, and overflow, while gravity pulls the colder and heavier air down and around to supply its place. The mechanical energy of the moving masses of air is exactly equal to the energy of the solar radiations consumed in maintaining the motion. The energy of the solar radiations absorbed by the air is transformed by expansion into the mechanical energy of the winds. Winds are merely transmuted sunshine.

600. *The Aqueous Circulation.* — In the aqueous circulation, water is continually passing into the atmosphere as vapor, then falling from the atmosphere as rain, and, finally, running in various streams down to the level of the ocean. This circulation is also maintained by energy absorbed from solar radiations. The solar heat absorbed by water converts it into vapor, and raises it into the atmosphere. When this vapor condenses in the atmosphere, gravity draws it to the surface of the earth, and to the level of the ocean. In the evaporation of the water the kinetic energy of the solar radiations is converted into the potential energy of molecular separation, and in the expansion by

which this vapor is raised into the atmosphere, into the potential energy of mechanical separation. In the condensation of the vapor in the atmosphere, its potential energy of molecular separation is transformed into the kinetic energy of heat, and in the fall of the rain to the earth and the descent of the water to the sea, its potential energy of mechanical separation is transformed into the kinetic energy of mechanical motion. The energy of the mountain stream which drives the mill came originally to the earth in the minute vibrations of the solar radiations, and was absorbed from these by water and air.

601. *The Circulation of Carbon.* — Carbon exists in the atmosphere in carbonic acid gas, a compound of carbon and oxygen. This gas is absorbed from the atmosphere by leaves of plants, in which it is decomposed by solar radiations, which are also absorbed by the leaves. The carbon is retained by the plant, and the oxygen is restored to the atmosphere. When vegetable substances are consumed by the natural process of decay, or as food in the bodies of animals, or as fuel in our stoves and furnaces, the carbon again unites with the oxygen and forms carbonic acid, which passes back into the atmosphere. Thus carbon is kept going round and round, from the atmosphere to plants and animals, and back again into the atmosphere. This circulation, like the other two, is maintained by energy obtained from solar radiation. By the decomposition of the carbonic acid in the leaves of the plant, the kinetic energy of the sunbeam is transformed into the potential energy of chemical separation ; and in the consumption of food and fuel, the potential energy thus required by carbon is converted into kinetic energy again. Animals derive all their energy from the food which they eat, and as this food is consumed in the body, its potential energy is converted partly into the kinetic energy of heat, and partly into the kinetic energy of mechanical motion.

The energy employed by man in thinking, writing, speaking, or in doing any kind of work whatever, came to the earth originally from the sun in the minute vibrations of the ether.

Coal is a vegetable substance, and its potential energy has been derived from solar radiations, and when we burn coal for fuel or coal gas for light, we are simply extracting from the coal the sunbeams that were ages ago absorbed by the leaves of plants and transformed into the potential energy of chemical separation.

602. *Source of Terrestrial Energy.* — Nearly every form of terrestrial energy is derived from the sun and comes to the earth in the solar radiations. The three chief agents for absorbing this energy and transforming it into a kind adapted for our use are water, air, and leaves of plants.

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